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AIRBORNE INVESTIGATIONS OF THE INCO AND FALCONBRIDGE STACK PLUMES, 1976-77

Report No. ARB-TDA 60-79

May 1979

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Ministry
of the
Environment

Ontario

The Honourable
Harry C. Parrott, D.D.S.,
Minister

Graham W. S. Scott,
Deputy Minister

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Ministry of the Environment,
Air Resources Branch,
Technology Development
and Appraisal Section.

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I. ABSTRACT:

Investigations of the rate of oxidation of SO_2 in the INCO 381 m Chimney plume were carried out using an instrumented helicopter in 1976 and 1977. Over a wide range of experimental conditions, the $SO_2 \rightarrow SO_4^=$ conversion rate was found to be relatively low - typically less than 0.4% hr^{-1}. Additionally, in-plume concentrations of various metals and sulfuric acid relative to SO_2 were determined at several downwind distances from the stack. Using a new analysis technique, estimates of metal and acid emission rates were made as was an assessment of the metal fallout pattern in the plume. Comparisons of the airborne and in-stack measurement data of the INCO 381 m chimney indicate the promise of this method. As a result of the apparently good correlation between the airborne and stack sampling methodologies, further investigations will be undertaken. By use of this method, it was found that the emissions from the Falconbridge stacks were quite substantial, e.g., iron (2.31 MTPD), arsenic (0.44 MTPD), copper (0.38 MTPD) and Nickel (0.27 MTPD). The results of the INCO 381 m chimney metal fallout studies indicate the process variability is extremely large and very sophisticated experimentation is required to quantify the pattern.

II. CONCLUSIONS AND RECOMMENDATIONS:

The airborne measurement results have been analyzed and the following conclusions and recommendations can be made:

- The particulate sulfur (sulfur compounds in particulate form) found in the INCO 381 m chimney plume seems to be mainly in the form of sulfuric acid, and is less than about 4% of the total plume sulfur, out to distances of about 100 km from the 381 m chimney. The SO_2 oxidation rate in the INCO 381 m chimney plume, over a wide range of temperature (-11 to 18°C) and relative humidity (34 to 87%) has been observed to be relatively low - typically less than 0.4% hr^{-1}. The observation was made up to a plume age of five hours. Extrapolation beyond these conditions is difficult and should be done with caution.

- No quantitative conclusion can be drawn regarding the reaction mechanism. Both homogeneous and heterogeneous mechanisms may be involved in the oxidation of $SO_2 \rightarrow SO_4^{=}$. However the data do suggest that the heterogeneous processes are important only at the initial stages after emission. There is also an indication that photochemical processes are important.

- The use of a new airborne measurement and analysis technique, the "Ratio Method", has been explored to obtain emission rates of metals and sulfuric acid in the INCO 381 m chimney, INCO Iron Ore Recovery Plant, and Falconbridge plumes. The technique has shown promise, however, it is not recommended in lieu of in-stack measurements, nor is it possible at this time assign any specific accuracy to the techniques. For the present, data collected by this means should be considered to be first estimates only.

- Based on the 1977 June airborne measurements, the metal particulate emissions from the Falconbridge stack were found to be quite substantial and the major emittants were iron (2.31 MTPD), arsenic (0.44 MTPD), Copper (0.38 MTPD) and Nickel (0.27 MTPD). As these quantities are not negligible compared to that of the INCO 381 m chimney, additional efforts will be made to more accurately quanitfy Falconbridge's emissions. These results may not be representative of the current emissions due to a new process adopted at Falconbridge since the summer of 1978.

- Attempts to measure from the INCO 381 m chimney plume, as a function of distance from the 381 m chimney were unsuccessful. The results indicate that process variability is extremely large and very sophisticated experiments would be required to quantify metal fallout patterns from the INCO 381 m chimney.

III. INTRODUCTION:

In recent years, the Ontario Ministry of the Environment has been carrying out a major programme to study environmental problems in the Subury area. The Air Resources Branch's participation in the Sudbury Environmental Study is focussed on quantifying emission sources and source strengths, and determining the fate of the pollutants emitted by the smelting activities in the Sudbury basin. As part of this effort, the Air Resources Branch has maintained airborne particulate matter and precipitation sampling networks, in addition to carrying out regular meteorological measurements and computer air quality modelling. The ultimate goal is to develop a computer model which, with the experimental input from the aforementioned studies, allows an accurate estimation of the large scale deposition field of the various emittants associated with the Sudbury industrial sources.

In addition to the results available from the ongoing regular programs, the computer model also requires specific information related to the physics and chemistry of the stack plumes. Therefore, intensive studies in the Sudbury area, primarily of the plume from the 381 m chimney of the INCO smelter at Copper Cliff, which is the major emittant source was carried out in Spetember, 1976, and again in 1977 in the months of February and June. These studies will hereafter be referred to as the September, February and June studies respectively. The Atmospheric Environment Service (AES) also participated in the September and June studies. All these studies focussed mainly on airborne measurements of sulfur compounds and metal particulates in order to yield data on SO_2 oxidation in the plume, pollutant emission rates and the metal fall-out pattern from the plume. Limited data were also collected on emission rates from the Falconbridge and the INCO Iron Ore Recovery Plant (IORP) stacks.

This account is a summary of the experimental procedures and a discussion of the results obtained from the studies.

During September of 1976, a companion airborne study was carried out, using a correlation spectrometer and continuous SO_2 analyser to estimate the SO_2 emission rate of the Falconbridge stacks. During the June study of 1977, a similar technique was employed to obtain both SO_2 emission and deposition rates from the INCO 381 m chimney plume. The results of these studies are given in other reports (1,2).

IV. EXPERIMENTAL:

An Alouette II helicopter was employed as the instrument platform in all three studies.

In the September study, only HiVol sampling of the plume proved useful. In both the February and June studies, low-volume sampling using 47 mm Nuclepore filter packs was also included. Each of the sampling systems involved a stack of 3 filters; the first one being a prefilter for particulates and the other two being impregnated filters stacked together for SO_2 sampling. In the HiVol sampling system, the prefilter was either a Whatman 41, Whatman 40 (for sulfates and metals) or Delbag (for H_2SO_4) and it was followed by 2 S and S (Schleicher and Schuell) filters impregnated with KOH-TEA solution. In the 47 mm packs, the prefilter was either a Whatman 41 (for $SO_4^=$ and metals) or Delbag (for H_2SO_4) and it was followed by 2 Whatman 41 filters impregnated with KOH-TEA solution . Two parallel 47 mm packs were used, so that simultaneous sampling of sulfuric acid and total sulfates could be carried out if desired. Sample air was conducted to the filters by means of isokinetic nozzles inserted in aluminum and teflon booms extending beyond the nose of the aircraft. Typical flow rates for the HiVol and 47 mm packs were approximately 1.25 and 0.015 m^3/min respectively.

A Sign-X SO_2 analyzer was operated during the sampling flights to aid in defining the physical boundaries of the plume. A typical flight included several horizontal runs of 15 to 30 passes through cross sections of the plume, perpendicular to its axis, over an interval of 1 1/2 to 3 hours. For the $SO_2 \rightarrow SO_4^=$ oxidation and metal fallout studies, the Superstack plume was typically sampled close to the stack, then at progressively further downwind distances. In some cases, the reverse sequence was used. Flight paths are indicated in Appendix 1 .

Except for the Whatman 40 and 41 filters which were split in halves for $SO_4^=$ and metal analyses, all other filters were used completely for either SO_2, $SO_4^=$ or H_2SO_4 determination.

For the September and February studies the isotope dilution method of Klockow (3) was used to analyze all sulfur species in the form of sulfate. The June samples were analyzed by ion chromatography (4) . The Whatman particulate filters were extracted with deionized water. All the SO_2-impregnated filters were extracted with 0.03% H_2O_2 solution to oxidize $SO_3^=$ to $SO_4^=$ except for the June study samples which were first water extracted before addition of H_2O_2. Delbag filters were first dissolved in benzaldehyde which was then filtered and extracted with deionized water. This differential extraction technique is based on the work by Leahy et al (5) who found that benzaldehyde selectively extracts sulfuric acid from other forms of sulfates.

The exposed Whatman 41 filters were analyzed for metals by the University of Toronto (September study samples) and McMaster University (February and June study samples), by instrumental neutron and photon activation analysis (6) .

Meteorological pilot balloons and minisondes were released hourly and tracked using double theodolites from ground level on all sampling days. They were needed to determine information on wind speed, wind direction, and temperature in the vertical. The wind speed measurements were essential for the calculation of $SO_2 \rightarrow SO_4^=$ oxidation rates. During the September 1976 study, the meteorological measurements at Copper Cliff and Falconbridge were made respectively by the staff of AES and MOE. During the February and June, 1977 studies, the meteorological measurements were made by MOE staff alone.

V. RESULTS AND DISCUSSION:

The following sections deal with the results of the plume SO_2 oxidation, the particulate and acid emission rate, and metal fallout experiments. It may be pointed out here that the SO_2 oxidation rate and metals fallout experiments involve certain assumptions about plume behaviour, most importantly:

(i) The pollutant emission rates are constant over the sampling period.

(ii) The plume is reasonably coherent and aloft so that the same portions of the plume are sampled at different downwind distances, and dry deposition of plume constituents does not occur, and

(iii) The $SO_4^=$ particulates are so small that insignificant gravitational settling occurs (i.e., the only process affecting the plume sulfate concentration is the oxidation of SO_2).

Assumptions (ii) and (iii) were probably acceptable for the present work because most of the flights were done when the plume was coherent and aloft. In addition, available information on $SO_4^=$ -bearing particulates shows that they are generally in the sub-micron size range (further work, in the INCO plume will be carried out during a particle sizing study in 1979). However, the available results on emission rates (see below) suggest that assumption (i) may not have been satisfied, and this should be borne in mind when considering the results to follow.

a) $SO_2 \rightarrow SO_4^=$ Conversion Studies in the INCO 381 Chimney Plume -

Results of the meteorological, as well as SO_2 and $SO_4^=$ measurements at different distances downwind of the stack for the September, February and June studies are given in Tables 1 to 5. The sampling locations tabulated in column 4 include distance from the INCO 381 m chimney and the bearing with respect to true north. In-flight measurements of temperature and relative humidity were made during the February and June studies. No similar measurements were made during the September study so the values of temperature and relative humidity shown in column 5 and 6 represent balloon sounding results. Wind speeds at plume level were estimated from the pibal results. The plume age of the sampled air parcel was calculated using appropriate methods of which details are given in Appendix 2. The last three columns in Tables 1 to 5 show the total amounts of S as $SO2$ and $SO_4^=$ sampled at the indicated locations, as well as the percentage of total sulfur in the form of SO_4. Due to the high plume sulfur concentrations, no corrections were necessary to account for SO_2 and $SO_4^=$ entrained from background air.

Not all of the experimental data are shown in Tables 1 to 5. In examining closely the data for SO_2 loading on the two impregnated filters, it was noted that in some cases the amount of SO_2 on the second filter was comparable to or greater than that on the first one. This suggested either breakthrough of SO_2 through the filter pack (and hence erroneously low concentrations) or direct physical transfer due to contact of the two filters stacked together. Breakthrough was suspected, because for these particular runs SO_2 loadings were generally high (and the capacity of the impregnated filter may have been exceeded), and also, the Sign-X SO_2 analyser records suggested much higher plume concentrations than measured by the filter pack.

Confidence in the SO_2 data was assured by comparing the SO_2 loading on impregnated filters and the simultaneous SO_2 loadings calculated from Sign-X SO_2 analyzer results. In the September study, the Sign-X instrument was not suitably calibrated and therefore no comparisons could be made. As a result, in Table 1, results from all runs are included. For the February and June studies, only runs where the Sign-X and filter pack agreed to within a factor of two are retained. These correspond to 88% (HiVol) and 47% (47 mm pack) of the February study, and 67% (HiVol) and 75% (47 mm pack) of the June study respectively.

Plots of % sulfur-as-sulfate against plume age showed a very large scatter. No quantitative conclusions could be made as to whether a first or second order mechanism better represents the data. The following method of presentation was therefore taken: the data were grouped into intervals of 0 - 0.5 hr, 0.51-1.0 hr., etc., and the average % S-as-$SO_4^=$ computed using all the values within each interval. At plume ages higher than about 2.5 hr., a larger interval was used due to the sparsity of data points. The data are presented in Tables 6 to 8 and the averaged % S as $SO_4^=$ values are plotted against averaged plume age in Figures 1 to 3. Also shown in the hatched area are the standard deviations of the data used in calculating the averages (plotted as points). In these figures, lines corresponding to 0%, 0.25%, and 0.50% hr^{-1} conversion have been drawn to indicate the general order of magnitude. It is clear from the plots that if a linear time dependence of the $SO_2 \rightarrow SO_4^=$ conversion is assumed within the limit posed by one standard deviation of all the data points, the overall oxidation rate cannot be greater than 0.25% hr^{-1}, 0.22% hr^{-1} and 0.42% hr^{-1} for the September, February and June studies. (This is consistent with the statistics generated by using all the individual data points for the three studies. The best fit yields oxidation rates of 0.014% hr^{-1}, 0.08% hr^{-1} and 0.22% hr^{-1} for the three studies respectively.) However, if the reaction rate is non-linear and is faster close in to the stack, the oxidation rate could be as high as 1.12% hr^{-1}, 0.83% hr^{-1}, and 1.14% hr^{-1} at the initial stages for the three studies respectively. This conclusion is further supported by direct measurement of sulfates as sulfuric acid using Delbag filters in the 47 mm filter pack. The results are summarized in Table 9 and 10 and Figure 4. The February sulfuric acid results are consistent with a $SO_2 \rightarrow SO_4^=$ conversion rate of 0.15% hr^{-1}. The best fit of the data points gives an oxidation rate of 0.082% hr^{-1}. What is clear from these studies is that the oxidation process of $SO_2 \rightarrow SO_4^=$ is quite slow in the INCO 381 m chimney plume and on the average, has a rate of less than about 0.4% hr^{-1}.

The oxidation rate of SO_2 in urban, power plant and smelter plumes has been studied rather extensively, especially in recent years (7-14). A range of conversion rates has been observed varying from less than 1% hr^{-1} to over 10% hr^{-1}. Both homogeneous gas-phase processes (8,9,15) and heterogeneous mechanisms involving particulates (10,11,16,17) have been proposed to explain the available data. The former are expected to depend on the solar radiation (18) and hence, the season and time of day of the measurements; the latter should be sensitive to such meteorological factors as temperature and relative humidity (16,17).

We have also looked for any evidence of heterogeneous processes, as indicated by a temperature and relative humidity dependence of the oxidation rate. The oxidation rate should increase with increasing relative humidity and decreasing temperature, according to the theory of Freiberg (16). The three studies considered here were carried out under conditions covering a wide range of relative humidity and temperature. Overall average oxidation rates from the data in Tables 1 to 5 are listed in Table 11, and plotted as a function of the relative humidity and temperature in Figures 5 and 6. The fact that there is no discernible trend in the data, suggests that heterogeneous mechanisms are unimportant. The negative oxidation rates have no physical significance but reflect the scatter of the data.

We have examined our data for any evidence of a dependence on solar radiation. All of the September flights were carried out in the morning, as were most of those in February, except for two during mid-day. In June, with the exception of two sunrise flights, all runs were carried out in the day time. If we make the reasonable assumption that radiation was on average higher during the latter runs than during all the others, then the slightly higher conversion rate observed in the June results (compare Figures 1-3) does suggest that photochemical reactions may be important.

The relatively low $SO_2 \rightarrow SO_4^=$ oxidation rate (0.4% hr^{-1}) observed in these studies is not surprising in view of the expected low concentrations of the active radicals (OH, HO_2, and CH_3O_2)

which are mainly responsible for SO_2 homogeneous oxidation. In an atmosphere which is quite free of NO_x and hydrocarbons, Calvert et al (15) have estimated oxidation rates of 0.4% hr^{-1}, 0.19% hr^{-1}, and 0.01% hr^{-1} respectively for reactions between SO_2 and OH, HO_2 and CH_3O_2 radicals. The major source of OH radicals is photolysis of ozone followed by reaction of atomic oxygen ('D) with water vapor. The production of singlet oxygen is dependent on light intensity. The low oxidation rate observed is a reflection of the low OH radical concentration and the slow mixing of ambient OH with the plume SO_2. The somewhat higher oxidation rate in June is consistent with the suggestion that photochemical processes are important.

The investigation most relevant to the present work is that of Lusis & Wiebe (7), who made similar measurements in the INCO 381 m chimney plume in September 1974 and June 1975. They found that within the first 100 Km of the stack, usually less than 10% of the plume sulfur is in the form of sulfate, and that the SO_2 oxidation rates were generally less than 3% hr^{-1} (typically about 1% hr^{-1}). No temperature and relative humidity dependence could be detected in the data, and a slight decrease in oxidation rate with plume age was suggested.

The present observations are in general agreement with those of Lusis and Wiebe. Our oxidation rates seem to be somewhat lower (less than about 0.4% hr^{-1} as compared to 1% hr^{-1}), but considering the accuracy of the measurements, this difference may not be significant. Lusis and Wiebe speculated that the conversion mechanism may be heterogeneous, though somewhat suppressed because of the high initial acidity of the emitted aerosols. The present results suggest that homogeneous gas-phase processes may also be important. It is interesting to note that Lusis and Wiebe report a few measurements which show that about 70% of the water-soluble aerosol sulfate in the plume was in the form of sulfuric acid near the chimney. A comparison of the values in Tables 7 and 10 of the present report suggest that most of the plume aerosol sulfur exists as sulfuric acid, even out to plume ages of several hours. Also, less than about 4% of the total sulfur is in particulate form (Tables 1 to 5), whereas Lusis and Wiebe reported some values as high as 10%.

Forrest and Newman (11) re-interpreted Lusis and Wiebe's data in terms of a second-order mechanism involving SO_2 and particulates. The validity of their analysis has been questioned by several workers (8,19) but there does seem to be some evidence in the data for the heterogeneous mechanism suggested by Newman and co-workers (11,13). For example, the SO_2 oxidation rate for all the runs is plotted against the plume age in Figure 7. There is some indication that the oxidation rate decreases as the plume age increases suggesting that the oxidation process is faster close to the stack and begins to level off with downwind distance.

The main results of the present investigation may be summarized as follows.

1. The particulate sulfur appears to be predominantly in the form of sulfuric acid (in droplet form or adsorbed on other particles), and has been found to be less than about 4% of the total plume sulfur, out to distances of about 100 Km from the 381 m chimney plume.

2. The SO_2 oxidation rate in the INCO 381 m chimney plume has been found to be low - typically, less than 0.4% hr^{-1}, which is somewhat lower than the earlier result of Lusis and Wiebe (7). This applies to the temperature and relative humidity ranges of -11 to 18°C and 34 to 87%, and to plume ages less than 5 hours. Extrapolation beyond these conditions is difficult and should be done with caution.

3. No quantitative conclusions can be made about the reaction mechanisms at the present time. Both homogeneous and heterogeneous reaction mechanisms may be involved in the oxidation of SO_2 - $SO_4^=$. However, the data suggest that if heterogeneous processes are important, they are only during the initial stages after emission. Later, photochemical processes may be important.

(b) Metals and Acid Emissions and Metals Fallout Rates -

As noted in the Introduction and Experimental Sections above, particulate matter from the INCO 381 m chimney plume was collected near the stack and at several downwind locations, with two objectives in mind:

(i) to explore the possibility of using such a technique to estimate metals and acid emission rates, where in-stack measurements are not possible or feasible, and

(ii) to see if there is any evidence of metals fallout from the plume.

In the September study, detectable amounts of the following elements were found by neutron and photon activation analysis: Ag, Au, Cr, Cd, Fe, Hg, Sb, Se, Zn, Co, Dy, Ba, Ti, Sr, In, I, As, Br, Mg, Cu, Na, V, Al, Mn, Cl, Ca, S, Pb and Ni. La, Sm, U and Sr could not be detected. In the February and June studies, the following elements were observed: Ag, As, Br, Co, Cr, Cu, Fe, Mn, Ni, Sb, Se, Zn and Hg. The γ-ray spectrum was also searched for Au, Ba, Ca, Cd, La, Mo, Sc, Sm, U and Zr but in no case was any of these metals detected.

This part of the report includes an estimate of the metal and acid emission rates from the INCO 381 m chimney and IORP and Falconbridge chimneys. It also includes an assessment of the importance of metals fallout from the Superstack plume.

(1) Airborne mass flux measurements of metals in the 381 m Chimney -

The most common technique for determining source emission rates of particulates is by in-stack ioskinetic sampling. Sometimes, this approach is not feasible or is difficult to carry out for practical reasons. In these field studies, we have explored the use of a new, alternative method, referred to as the "Ratio Method", to estimate particulate emissions. This method uses simultaneous airborne measurements of particulates and $S0_2$ and is dependent on a knowledge of $S0_2$ emission rates through either in-stack measurements or mass balance calculations. By relating the plume ratio of metal/$S0_2$ to the $S0_2$ emission rate, metal emission rates may be obtained (i.e., M/$S0_2$ x $S0_2$ emission rates). The present HiVol sampling method, with subsequent analyses of metals and $S0_2$, provided the necessary data. Only runs which show consistent HiVol-$S0_2$ and Sign-X-$S0_2$ are included (See Section V.a). Tables 12 to 14 summarize the metal-to-$S0_2$ ratios of the metals analyzed by INAA and IPAA techniques close to the stack for September, February and June studies. Only those samples with metal loadings at least two times above those of the filter blanks are included in the tables.

To determine if this technique is resonable, the metal/$S0_2$ ratios determined by airborne measurements are compared to those obtained by in-stack sampling in Tables 15 and 16.

The first column lists the parameters for which comparisons are available. The second and third columns list the number of airborne measurements and the corresponding average (± standard deviation) of the metal/SO_2 ratios. Similar in-stack measurements are given in columns four and five. A student-t statistical analysis was performed on these data and the last column indicates whether the airborne measurements are significantly different from those made in-stack, at the 95% confidence level. The airborne measurements were made typically over a 20-minute period. In September 1976, the in-stack measurement values are from two six-hour particulate tests and simultaneous SO_2 continuous monitor readings. The June 1977 values are based on two six-hour particulate tests and two two-hour acid tests and simultaneous SO_2 continuous monitor readings.

It is interesting to note from Tables 15 and 16 that, at the 95% confidence level, except for Na and As in the 1976 measurements and Zn and As in the 1977 measurements, all metal to SO_2 ratios obtained by both airborne and in-stack measurements are not statistically different. However, at the 98% confidence level, all ratios are not statistically different. The lower As/SO_2 ratio of the in-stack measurements could be a consequence of sampling and analytical problems associated with arsenic. It is noted that the average metal to SO_2 ratios are, in general, higher and lower for the airborne measurements in the September study and the June study respectively. This suggests possible systematic errors in sampling or analysis or extreme source variability. The metals were analyzed for the airborne and in-stack measurements by neutron activation analysis and atomic absorption techniques respectively. For some of the September results, the metal/SO_2 ratio measured in the plume could possibly be too high due to SO_2 breakthrough past the impregnated filters (- it was not possible to check September filter pack and Sign-X data for consistency - see Section V.a).

Using this technique, the average daily metal emission rates from the INCO Superstack can be estimated. Table 17 summarizes the metal/SO_2 ratios of the three studies and the averages of these values were used to calculate the mean daily metal flux. The major metals which are emitted are: Fe, Na, Pb, Al, Se, As, Cu, Zn, Mg, Ca, Ni, Cd, and Cr.

It should be noted that despite the general agreement between the airborne and in-stack measurements, the former measurements are usually associated with larger standard deviations. Therefore, the emission data calculated by this method should only be regarded as first estimates.

(2) Sampling in Falconbridge and INCO Iron Ore Recovery Plant Stack Plumes -

In-stack sampling at the INCO 381 m chimney has been carried out continuously over the past several years. However, in-stack measurements at Falconbridge and INCO Iron Ore Recovery Plant have not been feasible. Emission data from these sources are therefore very sparse or non-existent. For this reason, the "Ratio Method" was used as an alternative to obtain estimates of emissions from these sources.

Tables 18 and 19 summarize the airborne in-plume metal-to-SO_2 ratios, at Falconbridge during the February and June studies. There are two stacks at Falconbridge. Depending on the operating conditions, the results correspond to either the tall stack (sinter plant) only, the low stack (smelter plant) only or the combined stack emissions. Only runs corresponding to the combined emissions (see Table 19) are used for metal emission calculations. Results from Table 18, however indicate that M/SO_2 emission ratios from the low stack are in general smaller compared to those of the tall stack. This is consistent with the fact that the smelter stack is equipped with an electrostatic precipitator and the sinter stack is not. The upper limits of mean daily emission rate at Falconbridge are estimated based on SO_2 emission data and are given in Table 20. Based on the 1977 June data, the major metal emissions from the Falconbridge stack were iron (2.31 MTPD), arsenic (0.44 MTPD), copper (0.38 MTPD), and nickel (0.27 MTPD). Comparing the estimated Falconbridge and INCO 381 m chimney metal emissions (see Table 17) it is clear that metal particulate emissions from the two sources are comparable. One should remember that this conclusion is based on a limited number of samples, and possibly is an overestimate (because the two Falconbridge stacks did not operate all the time). They do suggest that metal particulate emissions are not negligible and should be further quantified. It should be noted that a new process has been adopted at Falconbridge since the summer of 1978 and a reduction of particulate emissions is expected. The results obtained so far may not be truly representative of the current emissions

Emissions from the INCO Iron Ore Recovery plant (IORP) stack are comprised of flue gases from the Iron Ore Recovery Plant, the three sulfuric acid plants of Canadian Industries Limited (CIL), and the Nickel Refinery plant. The Nickel Refinery Plant operates on a three stage (blow, charge, and reduction) cycle. In the September sampling, no information was recorded regarding the operating conditions. In the February sampling, a sample each was collected during the blow and charge stages. The corresponding metal/SO_2 ratios are calculated and are given in Table 21. Since emission information during the reduction stage is not available, the estimated daily Iron Ore Recovery Plant metal emission rates should be considered as first estimates only.

(3) Acid Emission Estimates from Airborne Measurements -

As noted earlier, there have been technical problems associated with the in-stack H_2SO_4 sampling method (a combination of modified EPA methods 5 and 8 (20)). It is therefore desirable to determine the acid emissions using an alternative appraoch. By the same principle discussed earlier in particulate sampling, H_2SO_4 was sampled, using a Delbag prefilter. This was followed by two impregnated cellulose filters, allowing simultaneous sampling of H_2SO_4 and SO_2. In the September study, the HiVol arrangement was used. In the February study, two 47 mm low-volume sampling packs in parallel were used instead. The 47 mm filter packs were also used in the June study. The June results are not useful because of problems encountered in chemical analyses. The results obtained close to the INCO 381 m chimney are summarized for the September and February studies in Tables 22 and 23 respectively.

The averages of the percentage ratio of $H_2S0_4/S0_2$ are respectively (1.9 ± 0.5)% and (1.7 ± 0.8)% for the September and February studies. The agreement is satisfactory considering the scatter in the data. If the average of the two studies is used to estimate sulfuric acid emissions from the INCO 381 m chimney plume, an average value of 56.7 MTPD is obtained.

Sulfuric acid has been measured direcly in the INCO 381 m chimney by the Source Assessment Unit of the Air Resources Branch several times in the past. The emission rates determined were respectively 15.2, 26.0, 42.9, and 9.0 MTPD for the years of 1973, 1974, 1975, and 1977. Due to the different problems encountered in both types of measurements, it is at present not possible to say whether the in-stack or airborne measurements are more accurate. Further work is planned in both of these areas.

Recent epidemiological and toxicological studies have suggested that sulfur compounds in the form of sulfite aerosols are associated with serious health hazards. A great deal of discussion regarding the existence of sulfite aerosols in smelter plumes has resulted. Eatough (21) has demonstrated the use of calorimetric techniques in determining the presence of in-plume sulfite complexes.

In the June 1977 study, Dr. A. Wiebe of the Atmospheric Environment Service analyzed the INCO 381 m chimney plume samples for sulfite species by use of ion chromatography and West Gaeke methods. No sulfites were detected in these plume samples (22). However, it was pointed out by Eatough (21) that the sulfite complexes are very labile and can oxidize in the plume with half life values on the order of minutes, suggesting that unless the samples are properly preserved, the chance of detecting sulfites in the sample is minimal.

Finally, some in-plume acid measurements were made at Falconbridge and INCO Iron Ore Recovery Plant. The Falconbridge H_2SO_4/SO_2 ratios as shown in Table 24 for the tall and low stacks are similar and the average of 0.38% is used to esti-a daily emission rate of 2.4 MTPD. In the case of INCO Iron Ore Recovery Plant there is no record as to during what stages (i.e., blow, charge or reduction) the samples were collected. Assuming the H_2SO_4/SO_2 ratio remains constant for all stages, the calculation H_2SO_4 daily emissions from the INCO Iron Ore Recovery Plant is 1.44 MTPD based on an averaged ratio of 1.27% (see Table 25). However, the above assumption has not been verified.

(4) Metal Fallout Results from the 381 m Chimney:

It has been pointed out in some recent vegetation soil and snow studies (23-26) in the Sudbury area that the metal concentrations fall off with distance from the source. In one case (25), this has been attributed to a Stokesian fallout of the metals from the plume. In addition, the high metal concentrations in the vicinity of the source can be a consequence of low level emissions, plume impingement and past accumulation of metals in the pre-381 m chimney period. In order to clarify the mechanism involved, the metal fallout pattern in the INCO 381 m chimney plume was studied. Metal particulates were collected on HiVol filters near the stack exit and at one or more downwind distances and analysis was carried out for selected metals.

To evaluate the metal fallout at specific downwind distances from the intact, elevated plume, SO_2 was chosen as the reference material because sedimentation of the gas is negligible in a coherent airborne plume. The results, expressed as metal-to-SO_2 ratios, are given in Tables 26 to 29 for the three studies respectively. The bracketed numbers (R) represent the metal/SO_2 ratios downwind from the stack normalized to the ratio near the stack. If there is metal fallout from the plume, the metal/SO_2 ratios should decrease with distance from the chimney. However, if there are local or external sources contributing to the metal content at downwind distances, a ratio of greater than unity is expected.

A few facts are quite apparent in the tables: (i) The ratios of (metal/SO_2) both near the source and far downwind are extremely variable; (ii) The normalized ratios, (R) are extremely variable and could change as much as an order of magnitude from run to run; and (iii) some runs show consistently $R > 1$ ratios, suggesting possible source variation and/or sampling and analytical errors.

The large scatter in the data was disappointing and may be due to sampling and analysis errors, or a failure of some of the basic assumptions inherent in this type of measurement (especially steady-state emission conditions over the period of measurement). It is evident that very sophisticated experiments are required to quantify metal fallout patterns from the 381 m chimney plume.

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TABLE 1: Results of September 1976 INCO 381 m Chimney Plume $SO_2 \rightarrow SO_4$ Study Using Hi-Vol Sampling Method

Date (Sept.)	Flt/Run	Time (local)	Location (Km/Deg)	Temp* (°C)	R.H.* (%)	Wind Speed ($M\ sec^{-1}$)	Plume Age (hr.)	S as SO_2 (μg)	S as $SO_4^=$ (μg)	Total S as $SO_4^=$ (%)
14	1/2	0920/0940	1.2:260°	16.5	70	8.3	0.04	29700	1200	3.88
	1/3	1000/1025	18.4:255°	16	69	9.5	0.54	16200	430	2.59
16	3/1	0905/0920	0.8:215°	11.5	72	4.4	0.05	159700	4230	2.58
	3/2	0940/1000	32:145°	11.5	74	3.5	2.52	9000	276	2.98
18	5/1	0745/0805	1.6:215°	16	61	7.4	0.06	70600	1056	1.47
	5/2	0825/0855	32:213°	14	64	7.4	1.2	21000	540	2.51
	5/3	0915/0955	56:215°	16	61	7.8	2.0	34700	620	1.76
18	6/2	1240/1330	1.6:215°	16	60	6.3	0.07	31900	678	2.08
	6/1	1150/1220	32:218°	12	68	8.0	1.11	22050	800	3.50
19	7/1	0735/0750	1.6:115°	15	63	11.0	0.04	31850	525	1.62
	7/2	0810/0835	32:150°	15	66	12.0	0.87	19700	537	2.65
	7/3	0900/0940	56:145°	18	63	8.6	1.88	20700	740	3.45
24	12/1+	0720/0740	0.8:100°	-1	77	7.4	0.03	40100	1120	2.72
	12/2+	0800/0820	16:100°	-3	78	7.9	0.56	22400	470	2.06
	12/3+	0840/0910	48:100°	-1	77	7.9	1.69	15850	480	2.94
	12/4+	0940/1010	104:100°	-2	80	7.9	3.66	11850	225	1.86

*Based on radiosonde or minisonde release from Copper Cliff, Ontario.
+Whatman 40 filters were used as pre-filter in this flight instead of Whatman 41 filters.

TABLE 2: Results of February/March 1977 INCO 381 m Chimney Plume $SO_2 \rightarrow SO_4$ Study Using Hi-Vol Sampling Method

Date (Feb/Mar)	Flt/Run	Time (local)	Location (Km/Deg)	Temp* (°C)	R.H.* (%)	Wind speed (M sec $^{-1}$)	Plume Behaviour	Plume age (hr.)	S as SO_2 (μg) 2-	S as SO_4 (μg) 4-	TOTAL S as $SO_4^{=}$ (%)
17	1/1	1325/1350	0.3:052°	-11	70	2.8	Fanning	0.03	218500	2487	1.13
	1/2	1415/1505	24.1:031°	-11	70	7.9	Fanning	0.85	50000	557	1.10
2	2/1	1134/1154	0.35:094°	-5.5	68	13.9	Coning	0.007	240000	3207	1.32
7	5/1	0920/0932	0.3:165°	-5	62	5.2	Coning	0.016	436000	3630.3	0.83
	5/2	0956/1034	18.8:180°	-7.5	51	5.7	Coning	0.91	148500	2077	1.38
7	6/1	1150/1232	23.1:164°	-7.5	49	4.0	Fanning	1.60	63000	493.7	0.78
8	8/1	0836/0847	0.1:088°	1	61	13.9	Fanning	0.002	1038500	10597	1.01
	8/2	0931/1003	34.3:060°	1.5	52	14.0	Fanning	0.68	108000	2307	2.09
9	10/1	1245/1256	0.1:220°	5.5	65	13.9	Coning	0.002	823500	8330.3	1.00
	10/2	1315/1353	8.3:241°	4.5	66	15.4	Fanning	0.15	49000	767	1.54
10	12/1	1033/1046	0.13:045°	7.5	48	12.0	Fanning	0.003	315500	2713.7	0.85
	12/2	1136/1159	19.7:055°	7	37	9.3	Fanning	0.59	49000	563.7	1.14
	12/3	1233/1305	49.9:061°	7.5	44	9.2	Fanning	1.51	87000	1017	1.16
12	17/2	1024/1034	0.1:325°	13	34	6.9	Coning	0.004	389000	5563.7	1.41
	17/1	0930/1000	12.8:331°	12	35	6.8	Coning	0.52	54500	633	1.15

* In flight measurements

TABLE 3: Results of February/March 1977 INCO 381 m Chimney Plume $SO_2 \rightarrow SO_4^=$ Study Using 47 mm Pack Sampling Method

Date (Feb/Mar.)	Flt/Run	Time (local)	Location (Km/Deg)	Temp* (°C)	R.H.* (%)	Wind Speed (M sec^{-1})	Plume Behaviour	Plume Age (hr.)	S as SO_2 (µg)	S as $SO_4^=$ (µg)	Total S as $SO_4^=$ (%)
2	2/1	1134/1154	0.35:094°	-5.5	68	13.9	Coning	0.007	3309	21.47	0.64
7	5/1	0920/0932	0.3:165°	-5	62	5.2	Coning	0.016	5819	45.33	0.77
7	6/1	1150/1232	23.1:164°	-7.5	49	4.0	Fanning	1.60	553.5	8.53	1.52
8	8/1	0836/0847	0.1:088°	1	61	13.9	Fanning	0.002	10367	127.67	1.22
	8/2	0931/1003	34.3:060°	1.5	52	14.0	Fanning	0.68	2068.5	25.53	1.22
10	12/2	1136/1159	19.7:055°	7	37	9.3	Fanning	0.59	883.5	8.9	1.00
	12/3	1233/1305	49.9:061°	7.5	44	9.2	Fanning	1.51	993.5	9.83	0.98
12	17/1	0930/1000	12.8:331°	12	35	6.8	Coning	0.52	1038.5	6.07	0.58

* In Flight Measurements

TABLE 4: Results of June 1977 INCO 381 m Chimney Plume $SO_2 \rightarrow SO_4^{=}$ Study Using Hi-Vol Sampling Method

Date (Jun.)	Flt/Run	Time (local)	Location (Km/Deg)	Temp* (°C)	R.H.* (%)	Wind Speed (M sec^{-1})	Plume Behaviour	Plume Age (hr.)	S as SO_2 (µg)	S as $SO_4^{=}$ (µg)	Total S as $SO_4^{=}$ (%)
3	1/1	0730/1030	0.55:115°	6.5	53	4.9	Bifurcating/ Fanning	0.02	97800	1760	1.77
	1/2	"	22.6:115°	5.0	56	8.2	Fanning	0.77	80400	1280	1.57
	1/3	"	55.4:115°	7.0	52	7.7	Fanning	1.99	6900	180	2.54
6	4/2	0655/1027	31.2:207°	0.5	61	10.4	Fanning	0.835	38950	840	2.11
7	5/2	0700/0954	32.0:210°	1.0	42	11.4	Fanning	0.78	40600	580	1.41
	5/3	"	52.2:203°	0.5	46	11.5	Fanning	1.26	6500	120	1.81
8	7/2	0704/1008	32.8:178°	1.0	64	9.9	Coning	0.92	24950	400	1.58
9	8/2	0645/1010	29.5:235°	1.5	58	7.8	Clouds at Plume Level/ Fanning	1.05	74950	1140	1.50
	8/3	"	56.7:222°	2.0	80	6.9	Fanning	2.28	35500	560	1.55
10	10/1	0701/1035	0.6:191°	6.5	82+	2.4	Rising Straight	0.07	78600	1360	1.70
	10/2	"	33.5:200°	6.0	72+	2.8	Fanning	3.35	58300	1240	2.08
	10/3	"	58.2:200°	6.0	56+	3.2	Fanning	5.06	21350	560	2.56
13	11/3	0648/1041	98.0:271°	9.0	54+	6.5	Fanning	4.22	53950	284	0.52
21	24/2	0525/0830	28.2:173°	10.0	87+	9.4	Fanning	0.83	47650	980	2.02
	24/1	"	50.1:174°	10.5	77+	8.6	Coning	1.61	32950	620	1.85
22	26/2	0458/0748	0.1:183°	10.5	-	6.9	Fanning	0.004	130950	900	0.68

* In flight measurements except noted by + (Ground level sonde release measurements)

- Not recorded.

Table 5: Results of June 1977 INCO 381m Chimney Plume $SO_2 \rightarrow SO_4^=$ Study Using 47 mm Filter Pack Sampling Method

Date (Jun.)	Flt/Run	Time (local)	Location (Km/Deg)	Temp* (°C)	R.H.* (%)	Wind Speed ($M\ sec^{-1}$)	Plume Behaviour	Plume Age (hr.)	S as SO_2 (µg)	S as $SO_4^=$ (µg)	Total S as $SO_4^=$ (%)
3	1/1	0730/1030	0.55:115°	6.5	53	4.9	Bifurcating/ Fanning	0.02	1782.5	20.0	1.11
	1/2	"	22.6:115°	5.0	56	8.2	Fanning	0.77	165	3.33	1.98
6	4/1	0655/1027	0.3:185°	0.5	61	9.3	Fanning	0.009	3570	38.3	1.06
	4/2	"	31.2:207°	0.5	61	10.4	Fanning	0.835	825	9.67	1.16
7	5/1	0700/0954	0.13:190°	1.0	36	12.0	Fanning	0.003	3410	23.33	0.68
	5/2	"	32.0:210°	1.0	42	11.4	Fanning	0.78	807.5	8.33	1.02
8	7/1	0704/1008	0.1:175°	0.0	51	13.9	Coning	0.002	4220	36.7	0.86
	7/2	"	32.8:178°	1.0	64	9.9	Coning	0.92	462.5	8.33	1.77
9	8/1	0645/1010	0.1:240°	1.5	61	9.3	Fanning	0.003	4545	50.0	1.09
	8/2	"	29.5:235°	1.5	58	7.8	Clouds at plume level/ Fanning	1.05	1250	15.0	1.19
	8/3	"	56.7:222°	2.0	80	6.9	Fanning	2.28	685	8.33	1.20
10	10/2	0701/1035	33.5:200°	6.0	72+	2.8	Fanning	3.35	2072.5	15.0	0.72
	10/3	"	58.2:200°	6.0	56+	3.2	Fanning	5.06	215	8.33	3.73
13	11/1	0648/1041	0.1:273°	10.0	70+	6.9	Fanning	0.004	5035	23.0	0.45
	11/2	"	30.2:270°	9.0	61+	9.3	Fanning	0.90	2815	27.7	0.97
21	24/2	0525/0830	28.2:173°	10.0	87+	9.4	Fanning	0.83	785	16.67	2.08
	24/1	"	50.1:174°	10.5	77+	8.6	Coning	1.61	602.5	8.33	1.36
22	26/2	0458/0748	0.1:183°	10.5	-	6.9	Fanning	0.004	3035	35.0	1.14

* In flight measurements except noted by + (Ground level sonde release measurements)

- Not recorded.

Table 6.

September 1976 - $SO_2 \rightarrow SO_4^=$ Oxidation Study Results

Flight/Run	Plume Age (hr)	% S as $SO_4^=$
1/2	.04	3.88
3/1	.05	2.58
5/1	.06	1.47
6/2	.07	2.08
7/1	.04	1.62
12/1	.03	2.72
Av. ± S.D.	0.05 ± 0.02	2.39 ± 0.883
1/3	.54	2.59
7/2	.87	2.65
12/2	.56	2.06
Av. ± S.D.	0.66 ± 0.19	2.43 ±0.325
5/2	1.20	2.51
6/1	1.11	3.50
Av. ± S.D.	1.16 ± 0.064	3.01 ± 0.700
5/3	2.00	1.76
7/3	1.88	3.45
12/3	1.69	2.94
Av. ± S.D.	1.86 ±0.156	2.72 ± 0.867
3/2	2.52	2.98
12/4	3.66	1.86
Av. ± S.D.	3.09 ± 0.806	2.42 ± 0.792

Table 7

February 1977 - $SO_2 \rightarrow SO_4^=$ Oxidation Study Results

Flight/Run	Type	Plume Age (hr)	% S as $SO_4^=$
1/1	HiVol	.03	1.13
2/1	HiVol	.007	1.32
5/1	HiVol	.016	.83
8/1	HiVol	.002	1.01
10/1	HiVol	.002	1.00
12/1	HiVol	.003	.85
10/2	HiVol	.15	1.54
17/2	HiVol	.004	1.41
2/1	47 mm	.007	.64
5/1	47 mm	.016	.77
8/1	47 mm	.002	1.22
Av. ± S.D.		0.02 ± 0.04	1.07 ± 0.29
1/2	HiVol	.85	1.10
5/2	HiVol	.91	1.38
8/2	HiVol	.68	2.09
12/2	HiVol	.59	1.14
17/1	HiVol	.52	1.15
17/1	47 mm	.52	.58
8/2	47 mm	.68	1.22
12/2	47 mm	.59	1.00
Av. ± S.D.		0.67 ± 0.15	1.21 ± 0.43
6/1	HiVol	1.60	.78
12/3	HiVol	1.51	1.16
6/1	47 mm	1.60	1.52
12/3	47 mm	1.51	.98
Av. ± S.D.		1.56 ± .052	1.11 ± 0.31

Table 8.

June, 1977 - $SO_2 \rightarrow SO_4^=$ Oxidation Study Results

Flight/Run	Type	Plume Age (hr)	% S as $SO_4^=$
1/1	HiVol	.02	1.77
10/1	HiVol	.07	1.70
26/2	HiVol	.004	.68
1/1	47 mm	.02	1.16
4/1	47 mm	.009	1.06
5/1	47 mm	.003	.68
7/1	47 mm	.002	.86
8/1	47 mm	.003	1.09
26/2	47 mm	.004	1.14
11/1	47 mm	.004	.45
Av. ± S.D.		0.01 ± 0.02	1.06 ± 0.43
1/2	HiVol	.77	1.57
4/2	HiVol	.835	2.11
5/2	HiVol	.78	1.41
7/2	HiVol	.92	1.58
24/2	HiVol	.83	2.02
4/2	47 mm	.835	1.16
1/2	47 mm	.77	1.98
5/2	47 mm	.78	1.02
7/2	47 mm	.92	1.77
24/2	47 mm	.83	2.08
4/2	47 mm	.90	.97
Av. ± S.D.		0.83 ±0.058	1.61 ±0.425
5/3	HiVol	1.26	1.81
8/2	HiVol	1.05	1.50
8/2	47 mm	1.05	1.19
Av. ± S.D.		1.12±0.121	1.50 ±0.310
1/3	HiVol	1.99	2.54
24/1	HiVol	1.61	1.85
24/1	47 mm	1.61	1.36
Av. ± S.D.		1.74 ± 0.219	1.92 ±0.593

Table 8. (Cont'd)

Flight/Run	Type	Plume Age (hr)	% S as $SO_4^=$
8/3	HiVol	2.28	1.55
10/2	HiVol	2.35	2.08
8/3	47 mm	2.28	1.20
Av. ± S.D.		2.30 ±0.040	1.61 ±0.443
10/3	HiVol	5.06	2.56
11/3	HiVol	4.22	.52
10/2	47 mm	3.35	.72
10/3	47 mm	5.06	3.73
Av. ± S.D.		4.42 ± 0.817	1.88 ±1.54

TABLE 9: Results of February/March 1977 INCO 381 m Chimney Plume $SO_2 \rightarrow H_2SO_4$ Study Using 47 mm Filter Pack Sampling Method

Date (Feb/Mar)	Flt/Run	Time (local)	Location (Km/Deg)	Temp* (^oC)	R.H.* (%)	Wind Speed ($M\ sec^{-1}$)	Plume Behaviour	Plume Age (hr.)	S as SO_2 (μg)	S as H_2SO_4 (μg)	Total S as H_2SO_4 (%)
17	1/2	1415/1505	24.1 : 031^o	-11	70	7.9	Fanning	0.85	347	2.97	0.85
2	2/1	1134/1154	0.35:094^o	-5.5	68	13.9	Coning	0.007	3378.5	20.24	0.65
	2/2	1219/1251	26.6:100^o	-5.5	72	13.4	Fanning	0.55	429	5.16	1.19
7	5/2	0956/1034	18.8:180^o	-7.5	51	5.7	Coning	0.91	616	9.57	1.53
7	6/1	1150/1232	23.1:164^o	-7.5	49	4.0	Fanning	1.60	548.5	2.87	0.52
	6/2	1300/1400	47.9:157^o	-5	51	4.4	Fanning	3.02	314	4.67	1.47
8	8/2	0931/1003	34.3:060^o	1.5	52	14.0	Fanning	0.68	1613.5	4.02	0.25
9	10/2	1315/1353	8.3:241^o	4.5	66	15.4	Fanning	0.15	658.5	12.8	1.91
10	12/1	1033/1046	0.13:045^o	7.5	48	12.0	Fanning	0.003	6346	68.25	1.06
	12/2	1136/1159	19.7:055^o	7	37	9.3	Fanning	0.59	723.5	11.72	1.59
	12/3	1233/1305	49.9:061^o	7.5	44	9.2	Fanning	1.51	1139	12.51	1.09
12	17/2	1024/1034	0.1:325^o	13	34	6.9	Coning	0.004	5318.5	20.70	0.39
	17/1	0930/1000	12.8:331^o	12	35	6.8	Coning	0.52	763.5	10.91	1.41

* In Flight Measurements

Table 10.

February , 1977 - Oxidation Study H_2SO_4 Results

Flight/Run	Plume Age (hr)	%S as H_2SO_4
2/1	.0007	.65
12/1	.003	1.06
17/2	.004	.39
10/2	.15	1.91
Av. ± S.D.	0.04 ± 0.07	1.00 ± 0.67
1/2	.85	.85
2/2	.55	1.19
5/2	.91	1.53
8/2	.68	.25
12/2	.59	1.59
17/1	.52	1.41
Av. ± S.D.	0.68 ± 0.16	1.14 ± 0.51
6/1	1.60	0.52
12/3	1.51	1.09
Av. ± S.D.	1.56 ± 0.06	0.81 ± 0.40
6/2	3.02	1.47

Table 11: Results on Average Conversion Rate, Plume Age, Temperature and Humidity

	Flt	$SO_2 \rightarrow SO_4^{=}$ (% hr^{-1})	Av. Plume Age (hr.)	Av. Temp. (^{o}C.)	Av. R.H. (%)
Sept.'76	1	-2.58	0.29	16.3	69.5
	3	0.35	1.29	11.5	73
	5	0.91	0.63	15	62.5
		0.15	1.03	15	61
		-0.94	1.60	15	62.5
	6	1.37	0.59	14	64
	7	1.24	0.46	15	64.5
		0.79	1.05	16.5	64.5
		1.0	0.95	16.5	63
	12	-1.25	0.30	-2	77.5
		0.79	1.13	-2	77.5
		0.13	0.86	-1	77
		-0.06	1.85	-2.5	79
		-0.24	2.11	-1.5	77.5
Feb.'77	1	-0.04	0.44	-11	70
(Hi-Vol)	5	0.62	0.46	-6.8	56.5
	8	1.59	0.34	1.3	56.5
	10	3.60	0.08	5.0	65.6
	12	0.49	0.30	10.7	42.5
		0.02	1.05	9.3	40.5
		0.21	0.76	10.6	46.0
	17	-0.50	0.26	12.5	34.5
(47 mm)	8	0	0.34	1.3	56.5
		-0.02	1.05	7.3	40.5
June '77	1	0.39	1.01	6.8	52.5
(Hi-Vol)		0.80	1.38	6.0	54.0
	5	0.83	1.02	0.8	44.0
	8	0.04	1.67	1.8	69.0
	10	0.12	1.71	6.3	77.0
		0.28	4.21	6.0	64.0
		0.17	2.57	6.3	69.0
	24	-0.22	1.22	10.3	82.0
(47 mm)	1	1.16	0.40	6.8	52.5
	4	0.12	0.42	0.5	61.0
	5	0.44	0.39	1.0	39.0
	7	0.99	0.46	0.5	57.5
	8	0.10	0.53	1.5	59.5
		0.01	1.67	1.8	69.0
		0.05	1.14	1.8	70.5
	10	1.76	4.21	6.0	64.0
	11	0.58	0.45	9.5	64.5
	24	-0.92	1.22	10.3	82.0

TABLE 12: Results of September 1976 INCO 381 m Chimney Metal/SO_2 Emission Ratios Using HiVol Sampling Method

Date (Sept)	Flt/Run	Location (Km/Deg)	SO_2 (µg)	Ag/SO_2 ($\times 10^{-5}$)	Fe/SO_2 ($\times 10^{-3}$)	Hg/SO_2 ($\times 10^{-5}$)	Sb/SO_2 ($\times 10^{-6}$)	Se/SO_2 ($\times 10^{-5}$)	Zn/SO_2 ($\times 10^{-4}$)	Ni/SO_2 ($\times 10^{-4}$)	Co/SO_2 ($\times 10^{-5}$)	As/SO_2 ($\times 10^{-4}$)	Br/SO_2 ($\times 10^{-6}$)	Cu/SO_2 ($\times 10^{-4}$)	Na/SO_2 ($\times 10^{-4}$)	Mn/SO_2 ($\times 10^{-6}$)	Ca/SO_2 ($\times 10^{-4}$)	Pb/SO_2 ($\times 10^{-4}$)
16	3/1	0.8:215°	319400	-	-	-	1.16	5.87	-	0.43	0.91	1.70	0.33	0.49	-	0.57	-	1.15
18	5/1	1.6:215°	141200	-	-	-	0.67	0.77	2.46	1.05	2.32	0.80	1.88	1.22	-	2.45	-	1.91
18	6/2	1.6:215°	63700	-	-	-	2.54	1.56	-	0.94	2.00	0.90	4.46	1.55	3.23	-	1.24	2.28
19	7/1	1.6:115°	63700	2.09	1.14	0.90	0.13	10.2	-	2.92	8.01	2.51	4.80	1.10	3.70	2.41	0.58	2.04
21	8/1	1.6:195°	96000	-	0.24	0.66	2.52	13.3	-	1.54	3.33	3.34	2.75	1.50	-	1.02	1.21	2.83
		Av.±S.D:	-	2.09×10^{-5}	$6.90 \pm 6.36 \times 10^{-4}$	$7.80 \pm 1.70 \times 10^{-6}$	$1.40 \pm 1.09 \times 10^{-6}$	$6.34 \pm 5.42 \times 10^{-5}$	2.46×10^{-4}	$1.38 \pm 0.95 \times 10^{-4}$	$3.31 \pm 2.76 \times 10^{-5}$	$1.85 \times 1.08 \times 10^{-4}$	$2.84 \pm 1.85 \times 10^{-6}$	$1.17 \pm 0.43 \times 10^{-4}$	$3.47 \pm 0.33 \times 10^{-4}$	$1.35 \pm 0.98 \times 10^{-6}$	$1.01 \pm 0.37 \times 10^{-4}$	$2.06 \pm 0.70 \times 10^{-4}$

TABLE 12: (Continued)

Date Sept	Flt/Run	Location (Km/Deg)	SO_2 (μg)	Au/SO_2 ($\times 10^{-7}$)	Cd/SO_2 ($\times 10^{-5}$)	Cr/SO_2 ($\times 10^{-4}$)	Sc/SO_2 ($\times 10^{-8}$)	Dy/SO_2 ($\times 10^{-7}$)	Ba/SO_2 ($\times 10^{-5}$)	Ti/SO_2 ($\times 10^{-5}$)	In/SO_2 ($\times 10^{-7}$)	I/SO_2 ($\times 10^{-6}$)	Mg/SO_2 ($\times 10^{-5}$)	V/SO_2 ($\times 10^{-6}$)	Al/SO_2 ($\times 10^{-4}$)	Cl/SO_2 (10^{-4})
16	3/1	0.8:215°	319400	-	-	0.17	2.39	3.41	0.29	0.50	0.57	-	0.20	1.30	0.25	1.93
18	5/1	1.6:215°	141200	0.60	-	0.39	3.29	0.97	0.05	-	1.11	-	15.0	1.21	1.56	2.32
18	6/2	1.6:215°	63700	4.08	-	0.94	-	1.11	-	1.43	0.98	-	21.3	2.60	1.96	12.3
19	7/1	1.6:115°	63700	4.18	-	0.13	8.48	7.13	-	2.00	1.70	6.66	-	1.43	3.69	21.4
21	8/1	1.6:195°	96000	2.77	8.71	1.09	-	7.42	-	0.56	2.08	3.21	6.85	2.65	1.25	6.50
		Av. ± S.D.:	-	$2.91 \pm 1.67 \times 10^{-7}$	8.71×10^{-5}	$5.44 \pm 4.44 \times 10^{-5}$	$4.72 \pm 3.29 \times 10^{-8}$	$4.01 \pm 3.14 \times 10^{-7}$	$1.70 \pm 1.70 \times 10^{-6}$	$1.12 \pm 0.72 \times 10^{-5}$	$1.29 \pm 0.60 \times 10^{-7}$	$4.94 \pm 2.44 \times 10^{-6}$	$10.84 \pm 9.23 \times 10^{-5}$	$1.84 \pm 0.72 \times 10^{-6}$	$1.74 \pm 1.26 \times 10^{-4}$	$8.89 \pm 8.15 \times 10^{-4}$

TABLE 13: Results of February/March 1977 INCO 381 m Chimney Metal/SO_2 Emission Ratios Using HiVol Sampling Method

Date (Feb/Mar)	Flt/Run	Location (Km/Deg)	SO_2 ($\times 10^5 \mu g$)	Ag/SO_2 ($\times 10^{-7}$)	Fe/SO_2 ($\times 10^{-4}$)	Hg/SO_2 ($\times 10^{-5}$)	Sb/SO_2 ($\times 10^{-7}$)	Se/SO_2 ($\times 10^{-5}$)	Zn/SO_2 ($\times 10^{-5}$)	Ni/SO_2 ($\times 10^{-5}$)	Co/SO_2 ($\times 10^{-6}$)	As/SO_2 ($\times 10^{-5}$)	Br/SO_2 ($\times 10^{-5}$)	Cu/SO_2 ($\times 10^{-4}$)	Mn/SO_2 ($\times 10^{-6}$)
17	1/1	0.3:052°	4.37	10.2	3.26	1.02	3.73	2.32	2.79	4.65	1.49	5.58	2.42	1.16	1.77
2	2/1	0.35:094°	4.80	2.54	1.02	7.11	0.85	1.27	3.81	2.54	0.93	2.11	-	0.38	-
7	5/1	0.3:165°	8.72	4.20	0.89	2.56	0.93	0.93	5.13	2.56	0.98	3.73	-	2.05	-
8	8/1	0.1:088°	20.5	5.09	1.96	0.17	0.39	2.94	4.50	3.52	1.41	8.81	1.33	0.59	1.14
10	12/1	0.13:045°	6.31	3.87	-	-	190+	1.22	2.58	3.54	0.97	7.09	1.80	0.48	-
12	17/2	0.1:325°	1.09	8.35	1.41	1.25	2.61	3.13	5.75	2.87	1.41	0.32	-	1.67	1.15
		Av.±S.D.:	-	5.71±2.94 x 10^{-7}	1.71±0.96 x10^{-4}	2.42±2.76 x10^{-5}	1.64±1.37 x10^{-7}	1.97±0.95 x 10^{-5}	4.09±1.27 x10^{-5}	3.28±0.80 x10^{-5}	1.20±0.26 x10^{-6}	4.61±3.17 x 10^{-5}	1.85±0.55 x 10^{-6}	1.06±0.69 x 10^{-4}	1.35±0.36 x10^{-6}

+ Excluded in calculations.

TABLE 14: Results of June 1977 INCO 381 m Chimney Metal/SO_2 Emission Ratios Using Hi-Vol Sampling Method

Date (June)	Flt/Run	Location (Km/Deg)	SO_2 (µg)	Ag/SO_2 ($\times 10^{-6}$)	Hg/SO_2 ($\times 10^{-5}$)	Sb/SO_2 ($\times 10^{-7}$)	Se/SO_2 ($\times 10^{-4}$)	Zn/SO_2 ($\times 10^{-5}$)	Co/SO_2 ($\times 10^{-6}$)	As/SO_2 ($\times 10^{-4}$)	Cu/SO_2 ($\times 10^{-4}$)
3	1/1	0.55:115°	195,600	0.62	8.71	2.08	1.25	3.32	1.46	2.08	0.42
10	10/1	0.6:191°	157,200	2.07	1.37	-	6.47	6.47	11.7	2.07	3.62
		Av. ±S.D.:	-	$1.35 \pm 1.03 \times 10^{-6}$	$5.04 \pm 5.19 \times 10^{-5}$	2.08×10^{-7}	$3.86 \pm 3.69 \times 10^{-4}$	$4.90 \pm 2.23 \times 10^{-5}$	$6.58 \pm 7.24 \times 10^{-6}$	$2.08 \pm 0.01 \times 10^{-4}$	$2.02 \pm 2.26 \times 10^{-4}$

TABLE 15. A COMPARISON OF SEPTEMBER 1976

METAL EMISSION DATA

		Metal/SO_2			
Metal	n	Airborne Measurements*	n	In Stack Measurements+	Statistically Different (95% Confidence level)
Fe	2	$(6.90 \pm 6.36)\ 10^{-4}$	2	$(6.25 \pm 2.53)\ 10^{-4}$	NO
Ni	5	$(1.38 \pm 0.95)\ 10^{-4}$	2	$(1.81 \pm 0.30)\ 10^{-4}$	NO
Co	5	$(2.31 \pm 2.76)\ 10^{-5}$	2	$(5.54 \pm 0.60)\ 10^{-6}$	NO
Cu	5	$(1.17 \pm 0.43)\ 10^{-4}$	2	$(1.99 \pm 0.95)\ 10^{-4}$	NO
Na	2	$(3.47 \pm 0.33)\ 10^{-4}$	2	$(1.68 \pm 0.21)\ 10^{-4}$	YES
Cr	5	$(5.44 \pm 4.44)\ 10^{-5}$	2	$(1.80 \pm 1.50)\ 10^{-6}$	NO
Ti	4	$(1.12 \pm 0.72)\ 10^{-5}$	2	$<(3.80 \pm 3.36)\ 10^{-6}$	NO
Mg	4	$(1.08 \pm 0.92)\ 10^{-4}$	2	$(1.86 \pm 0.27)\ 10^{-5}$	NO
Al	5	$(1.74 \pm 1.26)\ 10^{-4}$	2	$(2.26 \pm 0.37)\ 10^{-5}$	NO
Ca	3	$(1.01 \pm 0.37)\ 10^{-4}$	2	$(1.13 \pm 1.32)\ 10^{-5}$	NO
Pb	5	$(2.06 \pm 0.70)\ 10^{-4}$	2	$(9.58 \pm 3.71)\ 10^{-5}$	NO
Mn	4	$(1.35 \pm 0.98)\ 10^{-6}$	2	$(1.11 \pm 0.04)\ 10^{-6}$	NO
As	5	$(1.85 \pm 1.08)\ 10^{-4}$	2	$(1.15 \pm 0.65)\ 10^{-8}$	YES

* Based on twenty-minute airbourne measurements.

+ Based on six-hour in stack particulate tests and simultaneous SO_2 continuous monitor readings.

Ref : ARB-TDA-39-77 report, "Acid, Particulate and Particle Sizing Sampling at INCO Superstack, September, 1976" (1977)

TABLE 16: A COMPARISON OF JUNE 1977 METAL EMISSION DATA

Metal/SO_2

Metal	n	Airborne Measurements*	n	In Stack Measurements+	Statistically Different (95% Confidence level)
Zn	2	$(4.90 \pm 2.23)\ 10^{-5}$	4	$(8.74 \pm 1.31)\ 10^{-5}$	YES
Co	2	$(6.58 \pm 7.24)\ 10^{-6}$	4	$(11.6 \pm 8.50)\ 10^{-6}$	NO
As	2	$(2.08 \pm 0.01)\ 10^{-4}$	3	$(6.13 \pm 5.45)\ 10^{-5}$	YES
Cu	2	$(2.02 \pm 2.26)\ 10^{-4}$	4	$(3.49 \pm 1.05)\ 10^{-4}$	NO

* Based on twenty-minute airbourne measurements.

+ Based on 6-hour in-stack particulate tests and two-hour instack acid tests and simultaneous SO_2 monitor readings.

Ref: ARB-TDA 53-78 report, "Acid, Particulate and Particle Sizing Sampling at INCO Superstack, June, 1977" (1978)

Table 17: Determination of Metal Emission Rate at INCO 381 m Chimney

METAL	Metal/SO_2			Average M/SO_2	Emission Rate* (MTPD)
	September	February	June		
Ag	2.09×10^{-5}	5.71×10^{-7}	1.35×10^{-6}	7.61×10^{-6}	2.40×10^{-2}
Fe	6.90×10^{-4}	1.71×10^{-4}	-	4.31×10^{-4}	1.36
Hg	7.80×10^{-6}	2.42×10^{-5}	5.04×10^{-5}	2.75×10^{-5}	8.65×10^{-2}
Sb	1.40×10^{-6}	1.64×10^{-7}	2.08×10^{-7}	5.91×10^{-7}	1.86×10^{-3}
Se	6.34×10^{-5}	1.97×10^{-5}	3.86×10^{-4}	1.56×10^{-4}	4.93×10^{-1}
Zn	2.46×10^{-4}	4.09×10^{-5}	4.90×10^{-5}	1.12×10^{-4}	3.53×10^{-1}
Ni	1.38×10^{-4}	3.28×10^{-5}	-	8.54×10^{-5}	2.69×10^{-1}
Co	3.31×10^{-5}	1.20×10^{-6}	6.58×10^{-6}	1.36×10^{-5}	4.29×10^{-2}
As	1.85×10^{-4}	4.61×10^{-5}	2.08×10^{-4}	1.46×10^{-4}	4.61×10^{-1}
Br	2.84×10^{-6}	1.85×10^{-6}	-	2.35×10^{-6}	7.39×10^{-3}
Cu	1.17×10^{-4}	1.06×10^{-4}	2.02×10^{-4}	1.42×10^{-4}	4.46×10^{-1}
Na	3.47×10^{-4}	-	-	3.47×10^{-4}	1.09
Mn	1.61×10^{-6}	1.35×10^{-6}	-	1.48×10^{-6}	4.66×10^{-3}
Au	2.91×10^{-7}	-	-	2.91×10^{-7}	9.17×10^{-4}
Cd	8.71×10^{-5}	-	-	8.71×10^{-5}	2.74×10^{-1}
Cr	5.44×10^{-5}	-	-	5.44×10^{-5}	1.71×10^{-1}
Sc	4.72×10^{-8}	-	-	4.72×10^{-8}	1.49×10^{-4}
Dy	4.01×10^{-7}	-	-	4.01×10^{-7}	1.26×10^{-3}
Ba	1.70×10^{-6}	-	-	1.70×10^{-6}	5.36×10^{-3}
Ti	1.12×10^{-5}	-	-	1.12×10^{-5}	3.53×10^{-2}
In	1.29×10^{-7}	-	-	1.29×10^{-7}	4.06×10^{-4}
I	4.94×10^{-6}	-	-	4.94×10^{-6}	6.11×10^{-3}
Mg	1.08×10^{-4}	-	-	1.08×10^{-4}	3.40×10^{-1}
V	1.83×10^{-6}	-	-	1.83×10^{-6}	5.76×10^{-3}
Al	1.74×10^{-4}	-	-	1.74×10^{-4}	5.48×10^{-1}
Cl	8.89×10^{-4}	-	-	8.89×10^{-4}	2.80
Ca	1.01×10^{-4}	-	-	1.01×10^{-4}	3.18×10^{-1}
Pb	2.06×10^{-4}	-	-	2.06×10^{-4}	6.49×10^{-1}

*Based on the best estimated SO_2 emission rate of 3150 MTPD using 1973 to 1976 in-stack data.

TABLE 18: Results on February/March 1977 Falconbridge Stack Metal/SO_2 Emission Ratios Using HiVol Sampling Method

Date (Mar)	Flt/Run	Location (Km/Deg)	SO_2 ($\times 10^5$ ug)	Ag/SO_2^{2-} ($\times 10^{-7}$)	Fe/SO_2^{2-} ($\times 10^{-4}$)	Sb/SO_2^{2-} ($\times 10^{-7}$)	Se/SO_2^{2-} ($\times 10^{-6}$)	Zn/SO_2^{2-} ($\times 10^{-5}$)	Ni/SO_2^{2-} ($\times 10^{-5}$)	Co/SO_2^{2-} ($\times 10^{-6}$)
14	21/2*	0.1:135°	13.03	2.49	9.67	0.94	1.87	1.56	1.25	6.24
14	22/1+	0.1:125°	20.23	-	0.74	1.01	3.62	1.01	1.11	0.66

Date (Mar)	Flt/Run	Location (Km/Deg)	As/SO_2^{2-} ($\times 10^{-4}$)	Br/SO_2^{2-} ($\times 10^{-6}$)	Cu/SO_2^{2-} ($\times 10^{-4}$)	Mn/SO_2^{2-} ($\times 10^{-6}$)	Cr/SO_2^{2-} ($\times 10^{-6}$)
14	21/2*	0.1:135°	0.84	2.15	1.31	4.37	4.68
14	22/1+	0.1:125°	1.51	-	0.15	0.50	-

* Falconbridge tall stack (sinter plant)

+ Falconbridge low stack (smelter plant)

TABLE 19: Results on June 1977 Falconbridge Stack Metal/SO_2 Emission Ratios Using HiVol Sampling Method

Date (June)	Flt/Run +	SO_2 (μg)	Fe/SO_2 ($\times 10^{-3}$)	Hg/SO_2 ($\times 10^{-5}$)	Sb/SO_2 ($\times 10^{-7}$)	Se/SO_2 ($\times 10^{-5}$)	Zn/SO_2 ($\times 10^{-4}$)	Ni/SO_2 ($\times 10^{-4}$)	Co/SO_2 ($\times 10^{-5}$)	As/SO_2 ($\times 10^{-4}$)	Br/SO_2 ($\times 10^{-5}$)	Cu/SO_2 ($\times 10^{-4}$)	Mn/SO_2 ($\times 10^{-5}$)
21	25/1	46700	3.74	2.52	8.70	1.74	1.31	3.92	3.05	7.40	-	7.40	4.27
21	25/2	52500	4.65	2.94	-	1.55	0.93	5.81	3.41	5.42	-	6.97	2.63
21	25/3	124000	2.62	-	3.28	0.66	0.43	3.11	1.87	8.20	1.34	3.93	0.82
	Av.±S.D.:		$(3.67 \pm 1.02) \times 10^{-3}$	$(2.73 \pm 0.30) \times 10^{-5}$	$(5.99 \pm 3.83) \times 10^{-7}$	$(1.32 \pm 0.58) \times 10^{-5}$	$(0.89 \pm 0.44) \times 10^{-4}$	$(4.28 \pm 1.39) \times 10^{-4}$	$(2.78 \pm 0.81) \times 10^{-5}$	$(7.01 \pm 1.43) \times 10^{-4}$	(1.34×10^{-5})	$(6.10 \pm 1.89) \times 10^{-4}$	$(2.57 \pm 1.73) \times 10^{-5}$

+ Sampling was done in the combined plume from the tall and low stacks.

TABLE 20 : Determination of Metal Emission Rate at Falconbridge Stacks

Metal	Metal/SO_2	Emission Rate* (MTPD)
Fe	3.67×10^{-3}	2.31
Hg	2.73×10^{-5}	1.72×10^{-2}
Sb	5.99×10^{-7}	3.77×10^{-4}
Se	1.32×10^{-5}	8.30×10^{-3}
Zn	0.89×10^{-4}	5.60×10^{-2}
Ni	4.28×10^{-4}	2.69×10^{-1}
Co	2.78×10^{-5}	1.75×10^{-2}
As	7.01×10^{-4}	4.41×10^{-1}
Br	1.34×10^{-5}	8.43×10^{-3}
Cu	6.10×10^{-4}	3.84×10^{-1}
Mn	2.57×10^{-5}	1.62×10^{-2}

*Based on the best estimated SO_2 emission rate of 629 MTPD using Monthly mass balance data from 1973 to 1976.

TABLE 21: Determination of Metal Emission Rate at INCO Iron Ore Recovery Plant Stack*

Metal	Metal/SO_2				
	Mar.16/77	Mar.16/77	Sept.17/78	Average	Emission Rate (MTPD)
Ag	3.24×10^{-5}	1.73×10^{-5}	4.46×10^{-5}	$(3.14 \pm 1.37) \times 10^{-5}$	3.55×10^{-3}
Fe	1.19×10^{-3}	2.01×10^{-3}	2.94×10^{-3}	$(2.05 \pm 0.88) \times 10^{-3}$	0.23
Hg	8.52×10^{-5}	1.12×10^{-5}	1.01×10^{-5}	$(3.55 \pm 4.30) \times 10^{-5}$	4.01×10^{-3}
Sb	4.54×10^{-6}	0.47×10^{-6}	1.24×10^{-6}	$(2.08 \pm 2.37) \times 10^{-6}$	2.35×10^{-4}
Se	0.68×10^{-4}	0.23×10^{-4}	0.14×10^{-4}	$(3.50 \pm 2.89) \times 10^{-5}$	3.96×10^{-3}
Zn	4.54×10^{-5}	-	-	4.54×10^{-5}	5.13×10^{-3}
Ni	2.61×10^{-3}	0.70×10^{-3}	0.43×10^{-3}	$(1.25 \pm 1.19) \times 10^{-3}$	0.14
As	1.42×10^{-3}	0.28×10^{-4}	0.74×10^{-4}	$(8.13 \pm 5.74) \times 10^{-5}$	9.19×10^{-3}
Cu	6.81×10^{-3}	0.75×10^{-3}	0.57×10^{-3}	$(2.71 \pm 3.55) \times 10^{-3}$	0.30
Mn	-	1.31×10^{-5}	1.14×10^{-5}	$(1.23 \pm 0.12) \times 10^{-5}$	1.38×10^{-3}
Co	-	-	7.64×10^{-5}	7.64×10^{-5}	8.63×10^{-3}
Na	-	-	2.09×10^{-5}	2.09×10^{-5}	2.36×10^{-3}
Cr	-	-	2.67×10^{-4}	2.67×10^{-4}	3.02×10^{-2}
La	-	-	9.52×10^{-7}	9.52×10^{-7}	1.08×10^{-4}
Dy	-	-	4.72×10^{-8}	4.72×10^{-8}	5.33×10^{-6}
Ba	-	-	3.33×10^{-5}	3.33×10^{-5}	3.76×10^{-3}
Ti	-	-	1.98×10^{-5}	1.98×10^{-5}	2.24×10^{-3}
Mg	-	-	6.58×10^{-5}	6.58×10^{-5}	7.44×10^{-3}
V	-	-	1.49×10^{-6}	1.49×10^{-6}	1.68×10^{-4}
Al	-	-	2.90×10^{-4}	2.90×10^{-4}	3.28×10^{-2}
Cl	-	-	3.69×10^{-4}	3.69×10^{-4}	4.17×10^{-2}
Pb	-	-	3.84×10^{-4}	3.84×10^{-4}	4.34×10^{-2}

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* Based on the best estimated SO_2 emission rate of 113 MTPD from 1976 data.

TABLE 22: Results of September 1976 INCO 381 m Chimney Plume Acid Study Using Hi-Vol Sampling Method

Date (Sept.)	Flt/Run	Location (Km/Deg)	SO_2 (mg)	H_2SO_4 (µg)	H_2SO_4 / SO_2 (%)
14	1/1	1.0:120°/330°	28	0.4	1.43
14	2/1	0.2:180°/310°	241.8	4.1	1.70
16	3/3	0.2:140°/340°	303.3	7.4	2.44

TABLE 23: Results of February/March 1977 INCO 381 m Chimney Plume Acid Study Using 47 mm Pack Sampling Method

			Pack 1			Pack 2		
Date (Mar)	Flt/Run	Location (Km/Deg)	SO_2 (μg)	H_2SO_4 (μg)	H_2SO_4/SO_2 (%)	SO_2 (μg)	H_2SO_4 (μg)	H_2SO_4/SO_2 (%)
2/3	2/1	0.30:190^{o}/355^{o}	-	-	-	6757	62	0.92
3/3	3/2	* :130^{o}/250^{o}	-	-	-	7562	72.9	0.96
	3/3	0.27:110^{o}/250^{o}	9337	122	1.31	7535	124.3	1.65
	3/4	0.21:090^{o}/220	11137	111.4	1.00	-	-	-
6/3	4/1	* :040^{o}/190^{o}	10743	138	1.28	9082	104.4	1.15
7/3	7/1	0.21:020^{o}/190^{o}	6287	159	2.52	9217	152	1.64
8/3	8/1	0.06:170^{o}/330^{o}	32047	414	1.29	-	-	-
	9/1	0.06:170^{o}/340^{o}	19937	449	2.25	16937	188	1.11
	9/2	0.05:160^{o}/340^{o}	23717	689	2.91	-	-	-
	9/4	* :160^{o}/330^{o}	-	-	-	33907	844	2.49
9/3	11/1	0.03:150^{o}/300^{o}	39117	1203	3.08	-	-	-
	13/1	* :160^{o}/320^{o}	19337	573	2.96	-	-	-
10/3	12/1	0.12:160^{o}/310^{o}	12692	209	1.65	-	-	-
12/3	17/2	0.06:030^{o}/180^{o}	10637	63.4	0.60	-	-	-

* Not recorded, however very close to stack.

TABLE 24 : RESULTS OF FEBRUARY/MARCH 1977 FALCONBRIDGE PLUME ACID STUDY USING 47mm PACK SAMPLING METHOD

Date March	Flt/Run	Location (Km/Deg)	SO_2 (μg)	H_2SO_4 (μg)	H_2SO_4/SO_2 (%)
14	21/1 +	0.01:050°/220°	13637	35.3	0.26
14	22/1 *	0.01:040°/210°	28237	69.4	0.25
	22/2 *	0.01:040°/210°	7847	49.8	0.63

+ Tall Stack (sinter plant)

* Low Stack (smelter plant)

TABLE 25: Results of February/March 1977 INCO Iron Ore Recovery Plant Stack Plume Acid Study Using 47 mm Pack Sampling Method

Date (March)	Flt/Run	Location (Km/Deg)	SO_2 (μg)	H_2SO_4 (μg)	H_2SO_4/SO_2 (%)
12	19/1	0.02:050°/180°	5737	54.1	0.94
	19/2	0.01:050°/180°	11097	166	1.50
14	24/1	0.01:050°/200°	3975	54.7	1.38

TABLE 26: Results of September 1976 INCO 381 m Chimney Metall Fall-out Study Using HiVol Sampling Methods

Date (Sept.)	Flt/Run	Plume Age (hr.)	SO_2 (µg)	R (R_i/R_1)	Ag/SO_2 ($\times10^{-5}$)	As/SO_2 ($\times10^{-4}$)	Br/SO_2 ($\times10^{-6}$)	Co/SO_2 ($\times10^{-5}$)	Cu/SO_2 ($\times10^{-4}$)	Fe/SO_2 ($\times10^{-3}$)	Mn/SO_2 ($\times10^{-5}$)	Na/SO_2 ($\times10^{-4}$)	Ni/SO_2 ($\times10^{-4}$)	Sb/SO_2 ($\times10^{-6}$)	Se/SO_2 ($\times10^{-5}$)	Zn/SO_2 ($\times10^{-4}$)	Hg/SO_2 ($\times10^{-6}$)
16	3/1	0.05	319400		0.27	1.70	0.33	0.91	0.49	0.07	0.06	-	0.43	1.16	5.87	0.22	-
16	3/2	2.52	18000		2.7	1.60	10.4	3.34	2.46	-	1.66	3.84	3.12	3.86	5.56	-	-
				R2/R1	(9.8)	(0.94)	(31.3)	(3.7)	(5.0)	-	(29)	-	(7.2)	(3.4)	(0.95)	-	-
18	5/1	0.06	141200		0.15	0.80	1.88	2.32	1.22	0.17	0.25	-	1.05	0.67	0.77	2.46	0.92
18	5/2	1.2	42000		-	1.22	-	2.30	-	1.00	1.00	-	< 0.52	1.08	4.26	-	-
				R2/R1	-	(1.5)	-	(0.91)	-	(6.0)	(4.1)	-	(0.50)	(1.6)	(5.7)	-	-
18	5/3	2.0	69300		-	1.0	-	1.08	-	-	0.11	-	< 0.43	0.74	3.92	-	-
				R3/R1		(1.3)	-	(0.47)	-	-	(0.44)	-	(0.41)	(1.1)	(5.1)	-	-
18	6/2	0.07	63700		-	0.90	4.46	2.00	1.55	-	-	3.23	0.94	2.54	1.56	1.92	3.97
18	6/1	1.11	44100		-	0.87	9.02	1.40	1.09	-	1.15	0.69	1.27	0.81	6.48	-	-
				R2/R1	-	(0.96)	(2.0)	(0.70)	(0.70)	-	-	(0.21)	(1.3)	(0.32)	(4.2)	-	-
18	7/1	0.04	63700		2.09	2.51	4.80	8.01	1.11	1.14	0.24	3.70	2.92	0.13	10.2	1.40	9.01
18	7/2	0.87	39400		-	1.72	5.79	2.39	1.80	3.01	1.34	5.99	1.32	0.20	9.54	-	-
				R2/R1	-	(0.69)	(1.2)	(0.30)	(1.62)	(2.6)	(5.6)	(1.6)	(0.47)	(1.6)	(0.94)	-	-
18	7/3	1.88	41400		1.46	1.28	9.90	1.96	1.14	2.03	0.62	4.88	1.30	3.44	7.24	6.91	< 1.43
				R2/R1	(0.70)	(0.51)	(2.1)	(0.24)	(1.02)	(1.8)	(2.6)	(1.3)	(0.45)	(27)	(0.71)	(4.9)	(0.16)

Table 26 (Continued)

Date (Sept.)	Flt/Run	Plume Age (hr.)	SO_2 (μg)	R (R_i/R_1)	Au/SO_2 (x10^{-7})	Cd/SO_2 (x10^{-5})	Cr/SO_2 (x10^{-4})	Sc/SO_2 (x10^{-7})	Sm/SO_2 (x10^{-7})	Dy/SO_2 (x10^{-7})	Ba/SO_2 (x10^{-5})	Ti/SO_2 (x10^{-5})	In/SO_2 (x10^{-7})	I/SO_2 (x10^{-7})	V/SO_2 (x10^{-6})	Al/SO_2 (x10^{-4})	Cl/SO_2 (x10^{-3})	Ca/SO_2 (x10^{-4})	Pb/SO_2 (x10^{-4})
16	3/1	0.05	319400		0.30	-	0.17	-	-	3.41	0.29	0.50	0.57	0.06	1.30	0.25	0.19	-	1.15
16	3/2	2.52	18000		11.3	-	6.54	-	-	6.52	10.2	10.6	1.65	-	2.62	5.92	1.65	-	< 1.67
				R2/R1	(37.5)	-	(37.8)	-	-	(1.91)	(35)	(21.2)	(29.0)	-	(2.0)	(23.5)	(8.6)	-	(1.45)
18	5/1	0.06	141200		0.60	0.34	0.39	0.26	0.20	0.97	0.05	0.33	1.11	0.30	1.21	1.56	0.23	-	1.91
18	5/2	1.2	42000		7.62	-	1.56	-	-	1.04	6.04	1.86	-	-	1.48	4.24	0.45	-	< 0.36
				R2/R1	(12.7)	-	(4.0)	-	-	(1.1)	(130)	(5.6)	-	-	(1.2)	(2.7)	(1.9)	-	(0.19)
18	5/3	2.0	69300		2.66	-	0.48	0.64	-	1.19	-	-	1.24	-	0.92	1.69	0.17	2.14	< 1.45
				R3/R1	(4.4)	-	(1.23)	(2.4)	-	(1.2)	-	-	(1.12)	-	(0.76)	(1.1)	(0.73)	-	(0.76)
18	6/2	0.07	63700		4.08	0.63	0.94	-	-	1.11	-	1.43	0.98	90.1	2.60	1.96	1.23	1.24	2.28
18	6/1	1.11	44100		3.22	-	0.56	-		1.60	2.04	2.64	1.46	-	1.46	3.66	0.83	-	-
				R2/R1	(0.79)	-	(0.59)	-	-	(1.4)	-	(1.8)	(1.5)	-	(0.56)	(1.9)	(0.68)	-	-
18	7/1	0.04	63700		4.18	0.25	0.13	-	1.29	7.13	-	2.00	1.70	251	1.43	3.69	2.14	0.58	2.04
18	7/2	0.87	39400		7.82	-	0.78	1.48	-	4.95	3.63	2.41	1.66	7.21	2.31	6.07	2.28	4.5	5.18
				R2/R1	(1.9)	-	(5.8)	-	-	(0.69)	-	(1.2)	(0.98)	(.03)	(1.6)	(1.5)	(1.1)	(0.76)	(2.5)
18	7/3	1.88	41400		4.31	-	1.29	-	-	4.72	0.99	1.97	1.27	8.07	1.94	4.68	1.82	-	< 3.14
				R2/R1	(1. 03)	-	(9.9)	-	-	(0.66)	-	(0.99)	(0.75)	(.03)	(1.3)	(1.3)	(0.85)	-	(1.5)

TABLE 27: Results of February/March 1977 INCO 381 m Chimney Plume Metal Fall-Out Study Using HiVol Sampling Method

Date (Feb/Mar)	Flt/Run	Plume Age (hr.)	SO_2 ($x10^5$ μg)	R Ri/R1	Ag/SO_2 ($X10^{-7}$)	As/SO_2 ($X10^{-5}$)	Co/SO_2 ($X10^{-6}$)	Cu/SO_2 ($X10^{-4}$)	Fe/SO_2 ($X10^{-4}$)	Mn/SO_2 ($X10^{-5}$)	Ni/SO_2 ($X10^{-5}$)	Sb/SO_2 ($X10^{-7}$)	Se/SO_2 ($X10^{-5}$)	Zn/SO_2 ($X10^{-5}$)	Hg/SO_2 ($X10^{-5}$)
7	5/1	0.016	8.72		4.20	0.37	0.98	2.05	0.89	-	2.56	0.94	0.93	5.13	2.56
7	5/2	0.91	2.97		4.11	0.55	0.55	1.19	-	-	2.05	-	2.19	5.47	3.01
				R2/R1	(0.98)	(1.5)	(0.59)	(0.58)	-	-	(0.80)	-	(2.3)	(1.1)	(1.2)
8	8/1	0.002	20.77		5.09	0.88	1.41	0.59	1.96	0.11	3.52	0.39	2.94	4.50	0.17
8	8/2	0.68	2.16		-	1.51	0.08	0.09	-	-	-	-	0.75	6.59	-
				R2/R1	-	(0.17)	(0.05)	(0.16)	-	-	-	-	(0.26)	(1.5)	-
9	10/1	0.002	16.47		2.47	3.21	0.40	0.43	-	-	0.86	0.99	2.96	2.09	0.05
9	10/2	0.15	0.98		-	2.28	-	0.83	-	1.24	-	-	7.05	6.22	-
				R2/R1	-	(0.71)	-	(1.9)	-	-	-	-	(2.4)	(3.0)	-
10	12/1	0.003	6.31		3.87	7.09	0.97	0.48	-	-	3.54	1.90	1.22	2.58	-
10	12/2	0.59	0.98		-	1.04	2.49	1.66	-	-	-	-	4.98	4.56	1.70
				R2/R1	-	(0.15)	(2.6)	(3.4)	-	-	-	-	(4.1)	(1.8)	-
10	12/3	1.51	1.74		-	0.93	1.86	2.34	-	0.47	3.50	-	3.50	8.18	-
				R2/R1	-	(0.13)	(1.9)	(4.8)	-	-	(0.99)	-	(2.9)	(3.2)	-
12	17/2	0.004	7.78		8.35	3.19	1.41	1.67	1.41	0.12	2.87	2.61	2.13	5.75	1.25
12	17/1	0.52	1.09		-	2.05	-	3.26	-	0.82	-	-	5.97	5.59	-
				R2/R1	-	(0.64)	-	(1.9)	-	(7.1)	-	-	(1.9)	(0.97)	-

TABLE 28: Results of June 1977 INCO 381 m Chimney Plume Metal Fall-Out Study Using HiVol Sampling Method

Date	Flt/Run	Plume Age (hr.)	SO_2 (μg)	R (Ri/R1)	Ag/SO_2^{2-} (x10^{-6})	As/SO_2^{2-} (x10^{-4})	Co/SO_2^{2-} (x10^{-5})	Cu/SO_2^{2-} (x10^{-4})	Ni/SO_2^{2-} (x10^{-4})	Sb/SO_2^{2-} (x10^{-7})	Se/SO_2^{2-} (x10^{-4})	Zn/SO_2^{2-} (x10^{-4})	Hg/SO_2^{2-} (x10^{-4})
3	1/1	0.02	195,600		0.62	2.07	1.46	0.42	-	2.08	1.25	0.33	0.87
	1/2	0.77	160,800		1.26	1.89	1.99	1.89	0.63	-	1.01	2.28	1.19
				R2/R1	(2.0)	(0.91)	(1.4)	(4.5)	-	-	(0.8)	(6.9)	(1.4)
	1/3	1.99	13,800		-	2.94	-	2.94	-	-	2.06	-	-
				R3/R1	-	(1.4)	-	(7.1)	-	-	(1.6)	-	-
10	10/1	0.07	157,200		-	2.07	1.17	3.62	-	-	6.47	0.65	0.14
	10/2	3.35	116,600		-	3.48	0.14	0.90	0.24	-	1.05	0.67	0.38
				R2/R1	-	(1.7)	(0.12)	(0.25)	-	-	(0.17)	(1.0)	(2.9)
	10/3	5.06	42,700		28.6	11.47	-	5.16	-	-	3.14	3.14	-
				R3/R1	-	(5.5)	-	(1.4)	-	-	(0.49)	(4.8)	-

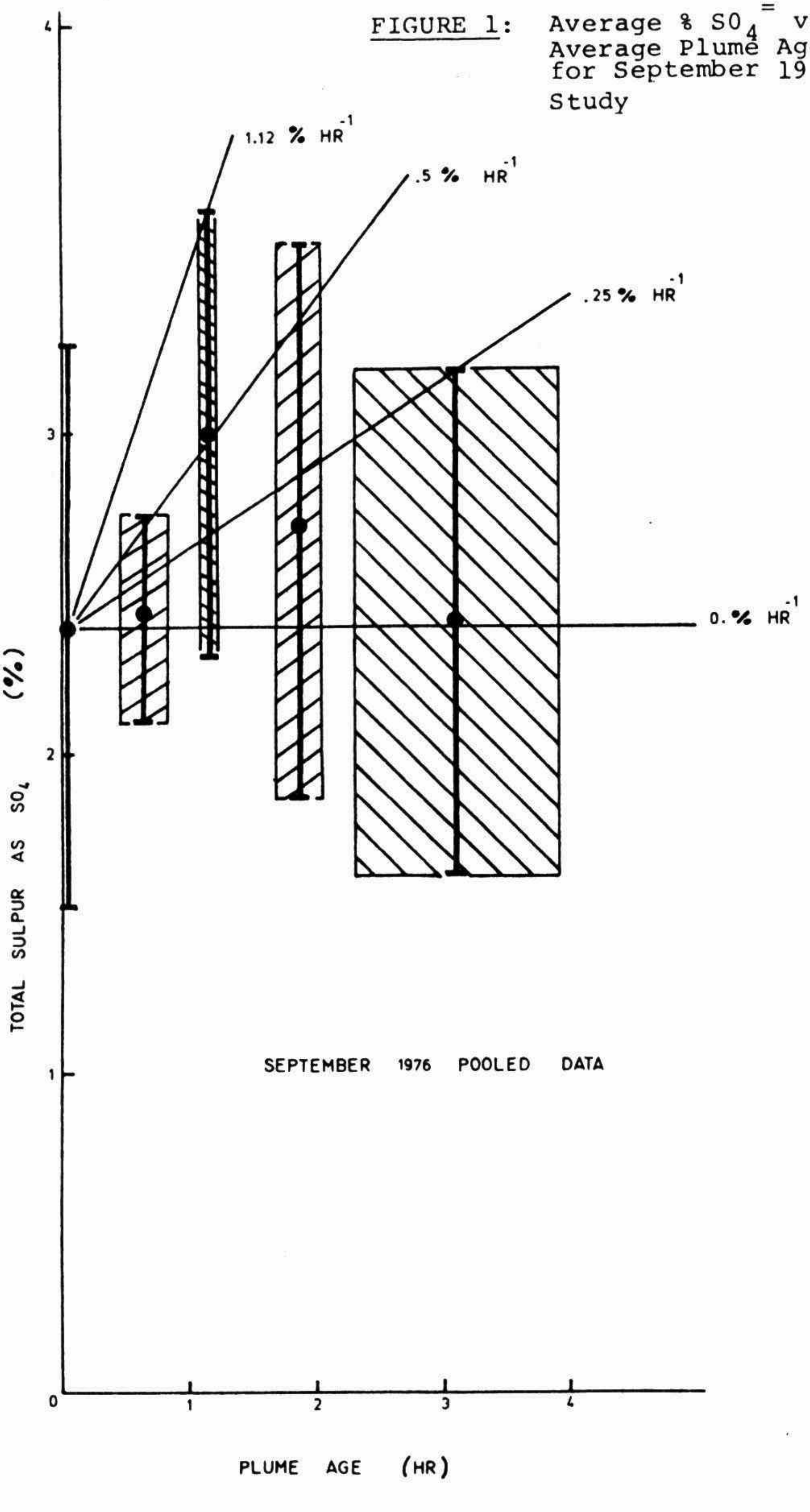


FIGURE 1: Average % $SO_4^=$ vs. Average Plume Age for September 1976 Study

FIGURE 2: Average % $SO_4^=$ vs. Average Plume Age for February 1977 Study

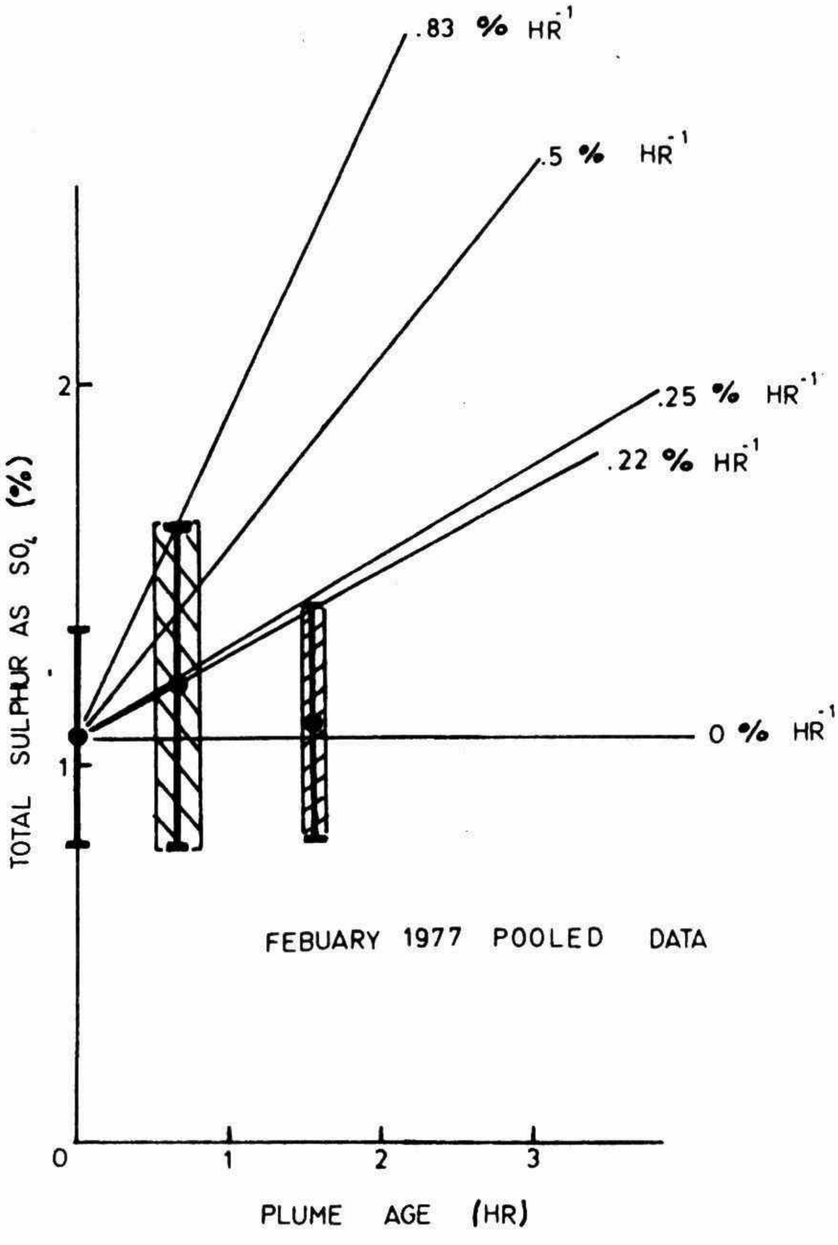


FIGURE 3: Average % $SO_4^{=}$ vs. Average Plume Age for June 1977 Study

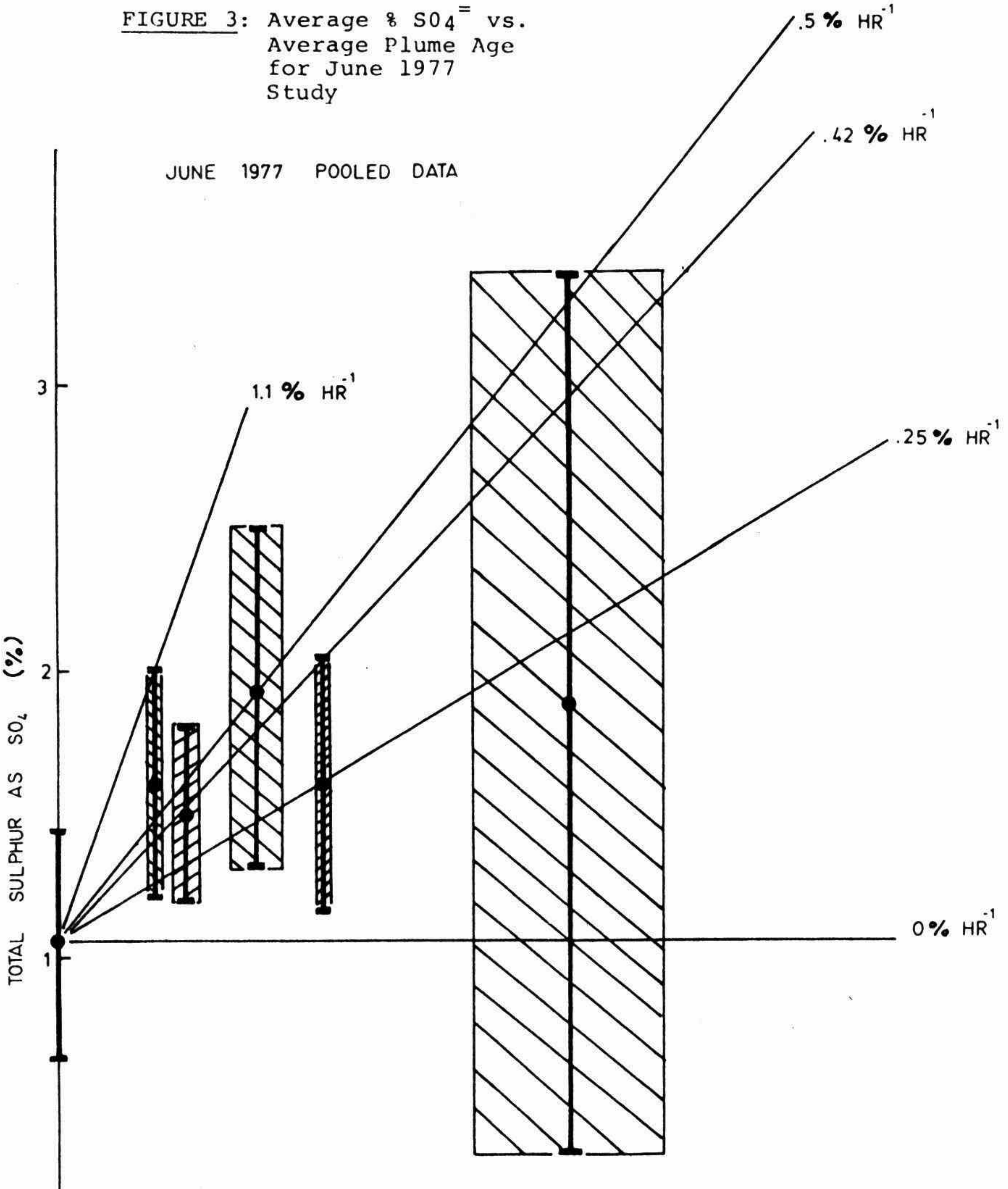
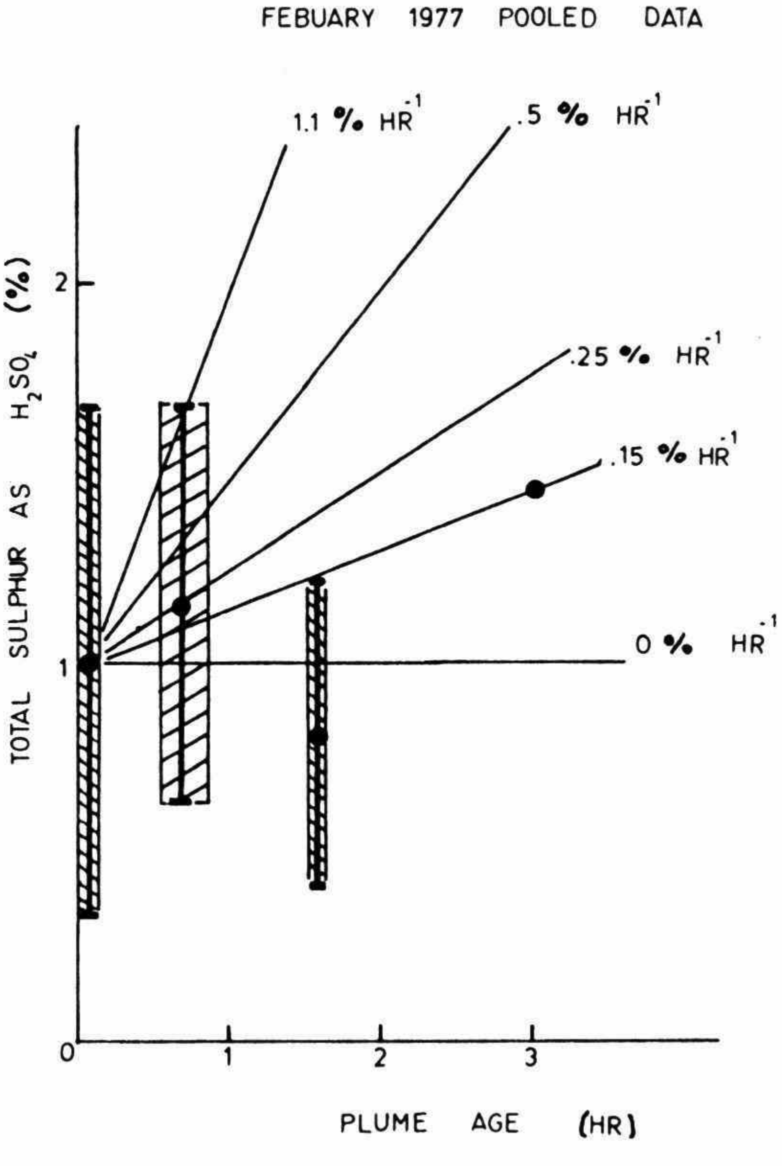


FIGURE 4: Average % H_2SO4 vs. Average Plume Age for February 1977 Study



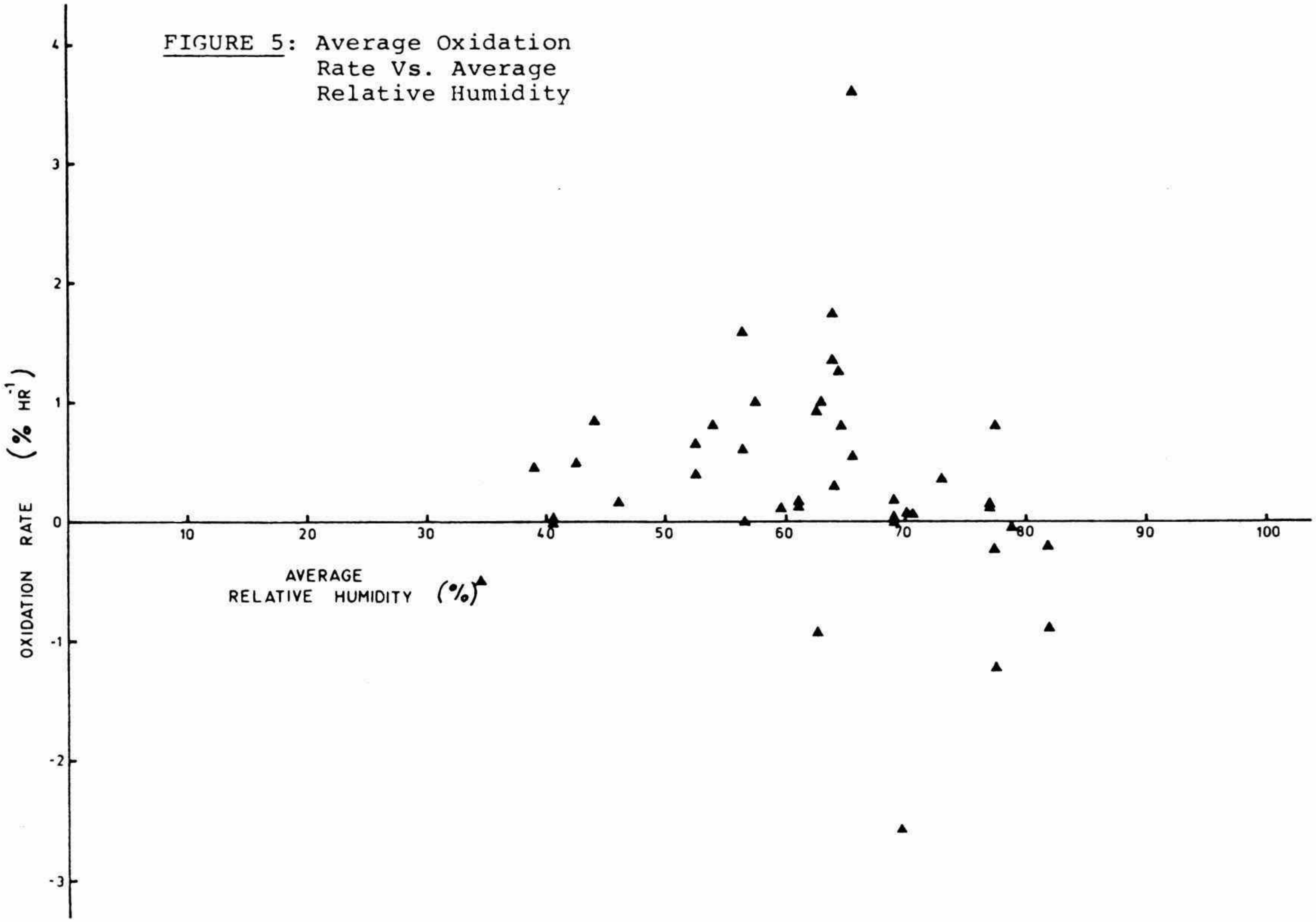


FIGURE 5: Average Oxidation Rate Vs. Average Relative Humidity

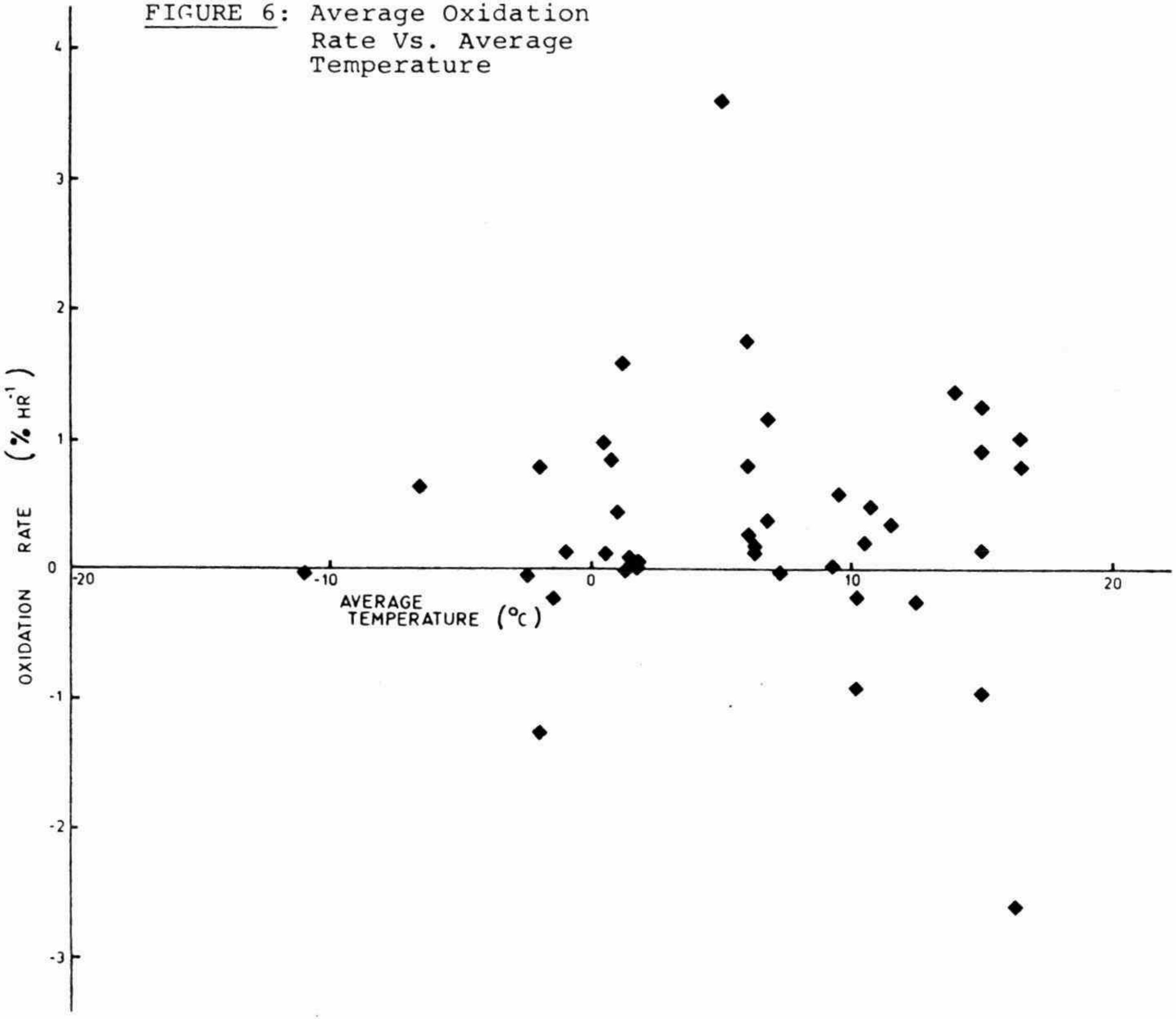


FIGURE 6: Average Oxidation Rate Vs. Average Temperature

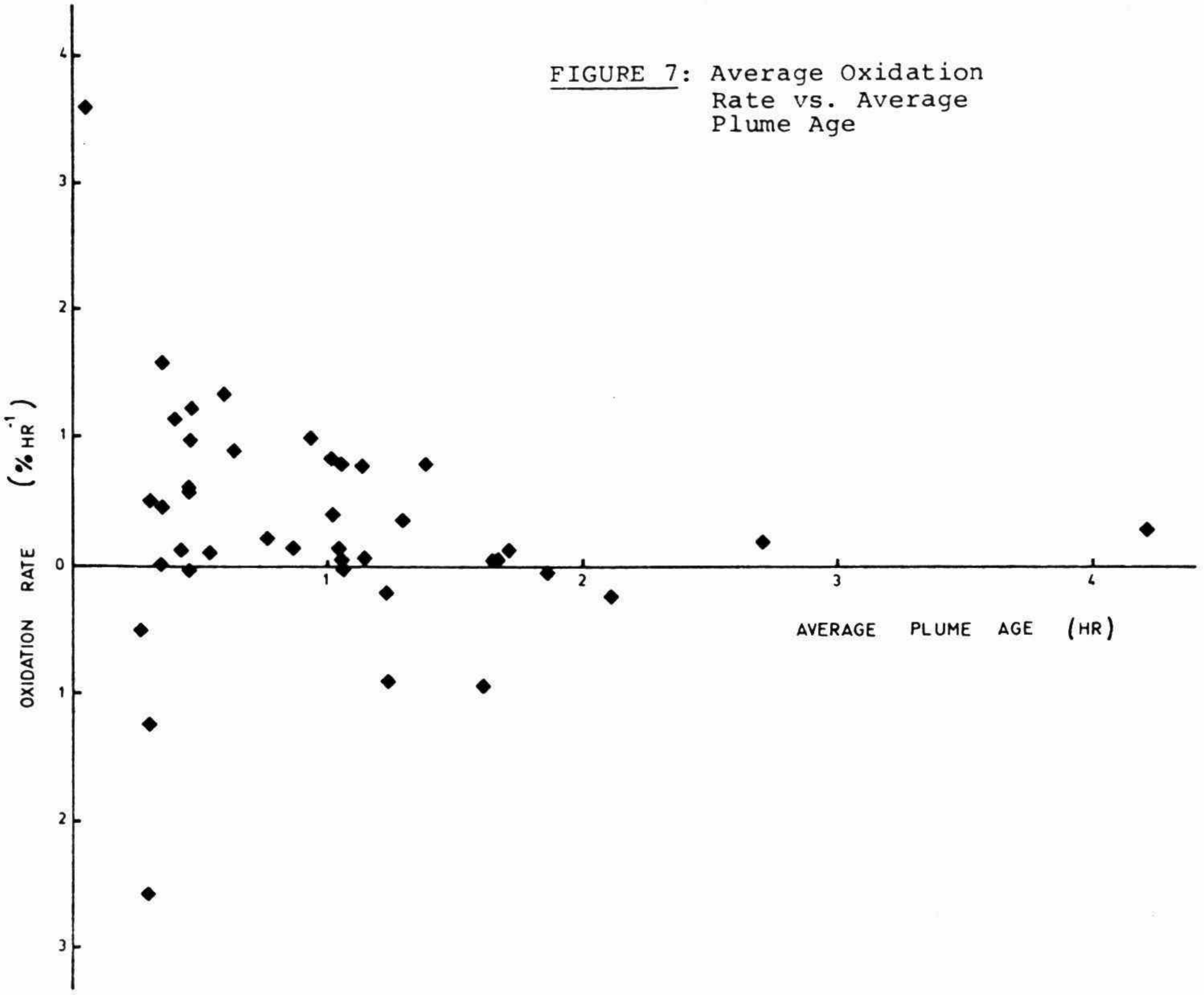


FIGURE 7: Average Oxidation Rate vs. Average Plume Age

APPENDIX 1

OXIDATION FLIGHT LOCATIONS

Flight locations are indicated by x....x for the February and June, 1977 Field Studies. In the September, 1976 field study, exact flight paths were not recorded so an indication of the general location of the flight path is given by a cross. The numbers on the maps refer to flight number/run number.

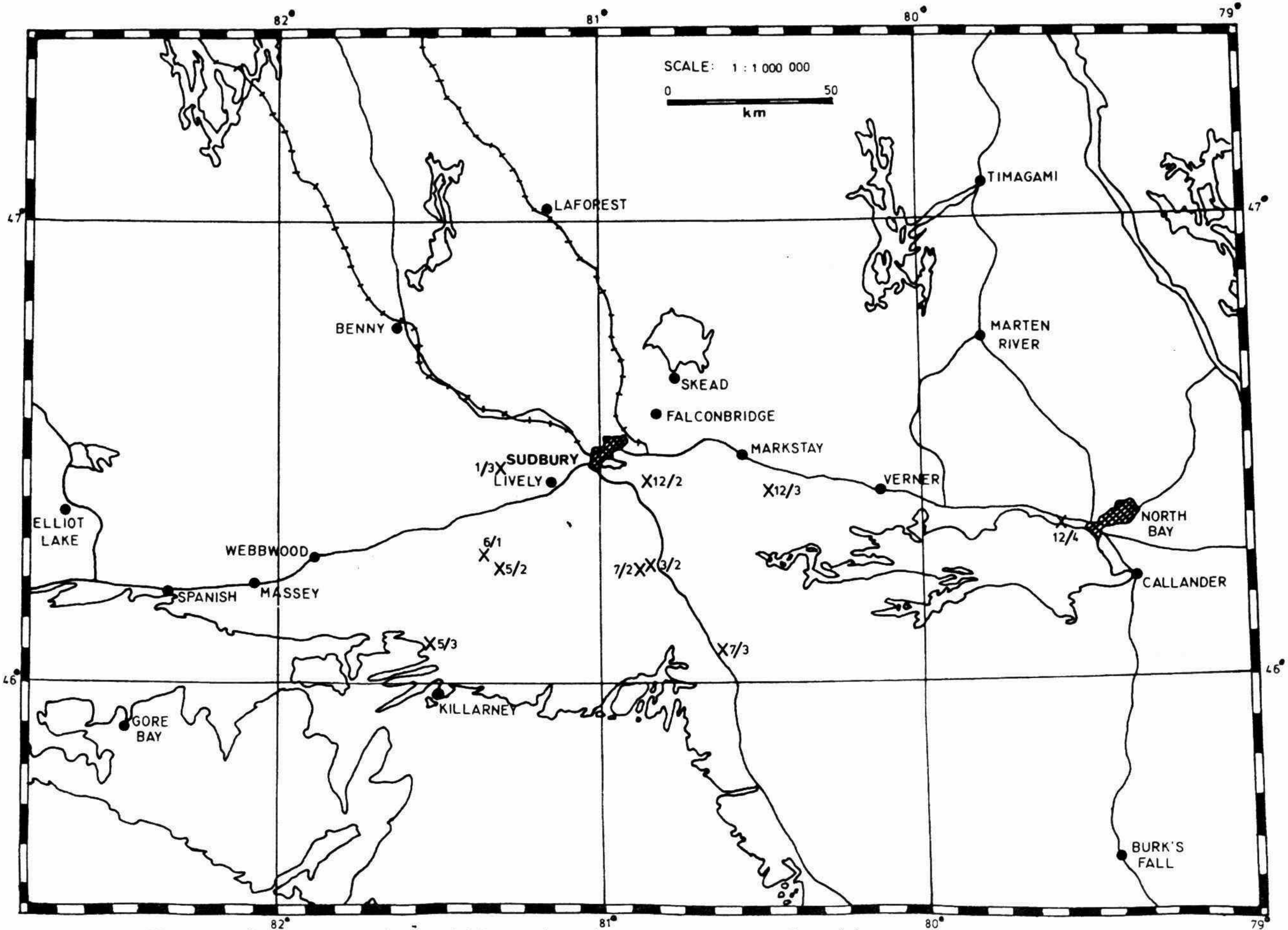


FIGURE A1-1: September, 1976 Oxidation Flight Path Locations

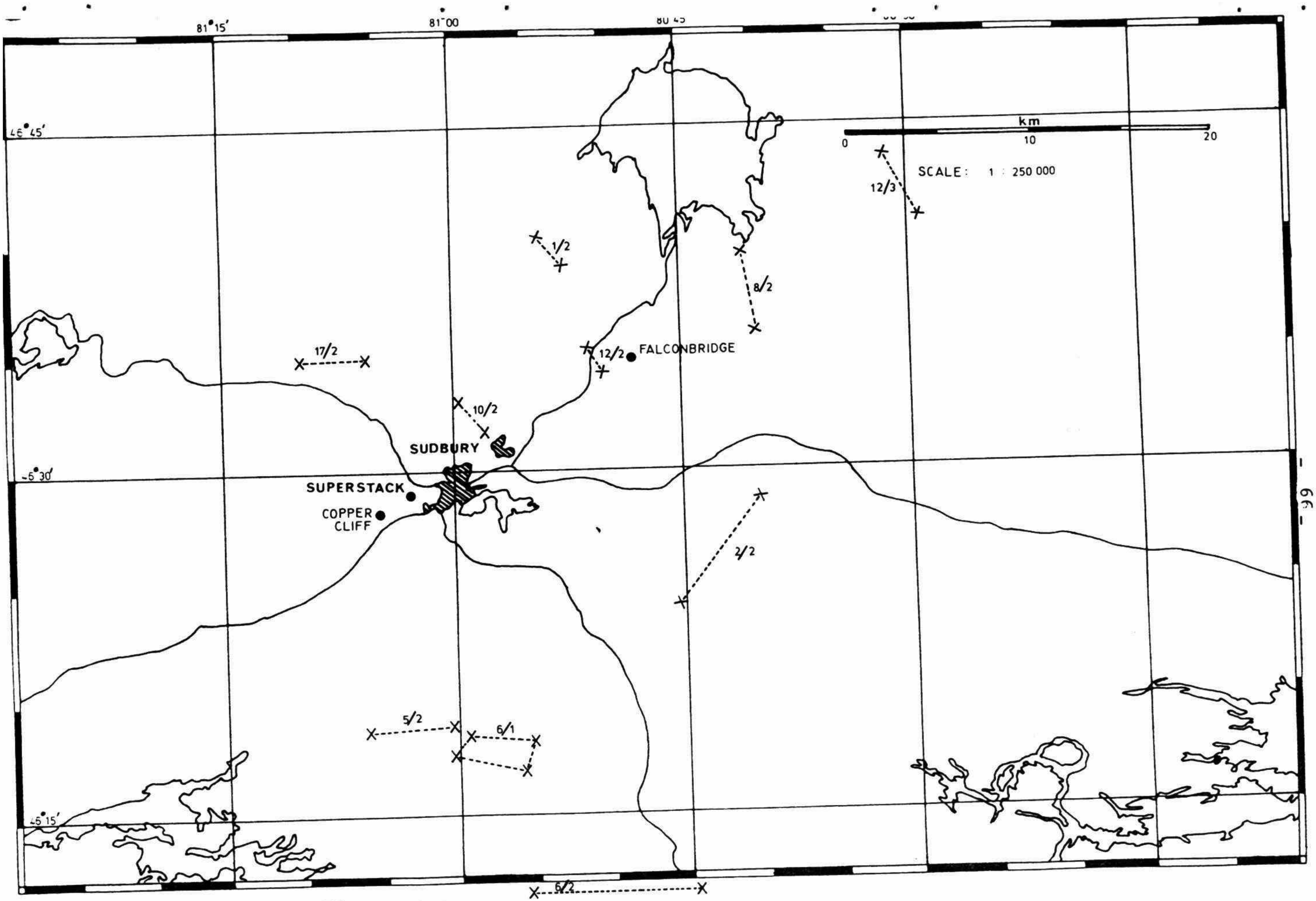


Figure A1-2: February 1977 Oxidation Flight Paths

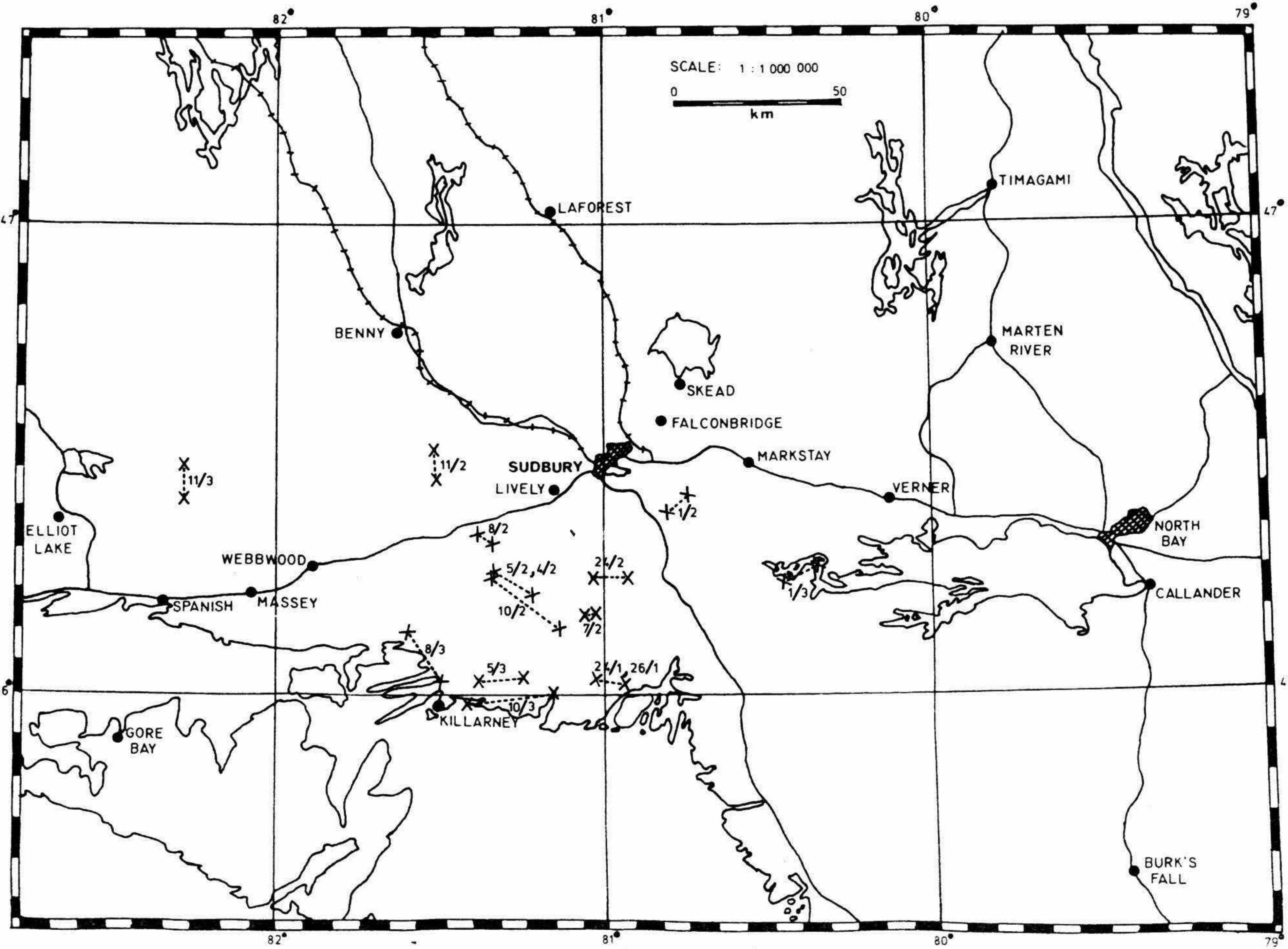


FIGURE A1-3: June 1977 Oxidation Flight Paths

APPENDIX 2

Plume Lifetime Estimates
For Oxidation Runs
For The
Sept./76, Feb-/77 and June/77 Field Studies

Plume Lifetime Calculations

Introduction:

The calculation of SO_2 to $SO_4^=$ plume oxidation rates depends on both the measurement of SO_2 and $SO_4^=$ in the plume at different downwind distances from the source and the calculation of plume age for each sampled parcel of the plume. The calculation of plume age is typically made from a knowledge of the distance from the sampling location to the stack and the speed of the wind responsible for transporting the plume to the sampling location. This calculation is complicated by the variation of the wind field with height and the resulting dependence of the rate of transport of the plume on its elevation above ground level. The overall accuracy of any plume age and subsequent oxidation rate calculations is, therefore, dependent on the accuracy of wind speed measurements. For the plume lifetime calculations discussed in this report, the wind measurements were obtained from meteorological pilot balloons tracked from the ground or, when these data were not available, from meteorological tower or trajectory data. The methods and results of the plume age calculations are discussed in this report.

Description:

Four different methods of calculating plume lifetimes were used. These methods are summarized below and Table A2-1 indicates which methods were used for the individual flights.

Method 1: This method was most widely used in the calculations. The method is called the "backward iteration technique", and, in general, consists of iterating a parcel of sampled plume backwards in time while changing the wind speed depending on the time and the height of the parcel. Details of the analysis are as follows:

i) At each sampling position, the average height of the sample plume parcel was calculated as the average height of all 15 passes at that position.

ii) The distance from the Superstack to each sampling position was calculated using the traverses marked on maps for the June and February, 1977 traverses and using operators calculations for the September, 1976 study. Using maps, the distances to the extreme limits of the traverses could be calculated as well as to the centre of the traverse.

iii) The average height of each sampling cross-section and its distance from the stack were plotted. Since the plume height typically increased from the first cross-section to the second and decreased from the second to the third positions, a characteristic height was interpolated for those portions of the plume between measured points, e.g.,

Distance From Stack	Representative Height of Plume (MSL)
0-5 Km	500 m
5-10 Km	650 m
10-15 Km	800 m
15-20 Km	950 m
20-30 Km	900 m
30-40 Km	850 m

iv) Wind direction and wind speed at each characteristic height were calculated from the pilot balloon data before and during the sampling period.

v) Wind speeds were plotted as a function of time for each characteristic height of the plume. A sample of the plot is shown as Figure A2-1.

vi) The times of the sampling runs were marked on the graphs and divided into 5,10 or 20 minute sub-parcels. Longer parcels were used for longer sampling periods.

vii) Each parcel was moved back in time using the wind speed between adjacent parcels. When a parcel had travelled back far enough that the representative height was no longer valid, it was iterated to the next representative height. When each parcel had travelled through all representative heights and had arrived at the stack, then the total travel time for each parcel was calculated. An average lifetime for the sampled plume was calculated as an average of all individual parcel lifetimes. Because the wind speed typically changed with time, the minimum and maximum lifetimes of the plumes were often significantly different than the average lifetime.

Method 2: Method 2 was based on the following equation for motion under constant acceleration:

$$D = U_0 t + \tfrac{1}{2} a t^2$$

where D = distance travelled in time t

a = rate of change of wind speed with time

U_0 = wind speed at the start of interval t.

t = plume lifetime

The distance, D, travelled by a plume parcel at any reference height was obtained from the plots as were the values "a" and "U_0". Each parcel lifetime was calculated and all lifetimes were averaged in a manner similar to Method 1.

Method 2 was simply a more sophisticated variation of Method 1 but was considerably more time consuming. As a result it was used for only two plume lifetime calculations.

Method 3: When insufficient pibal data were available for plume lifetime calculations, two other sources of data were used. They were:

(1) 850 mb. trajectory analyses and (2) pibal data extrapolated forward in time and used in conjunction with MOE tower data.

A comparison of 850 mb. trajectories with pibal data suggests that the trajectory analysis is very accurate if winds are relatively constant in direction. This was the case in all plume lifetime calculations using trajectory analyses.

Method 4: This method was used as a check on all other plume lifetime calculations. It is the method used by AES in all previous oxidation work. AES's method consisted of averaging the wind speed at the height of the plume traverses for the total (approximate) time that the plume was in the atmosphere. Using this one average velocity, $\bar{U}$, the plume lifetime of the parcel was calculated as $\bar{T} = D/\bar{U}$. When this method was used for the MOE oxidation runs, the wind speeds were averaged graphically over all heights and times of the plume's life. In all cases, the plume lifetime calculations fell well within the extremes of the plume lifetime calculations made using Method 1. For the cases sampled, the plume lifetime calculated from the averaged wind speed were typically within 10% of the average plume lifetime calculated using Method 1.

The philosophy behind using this method is based on the knowledge that pibal flights provide instantaneous values of the wind field and often do not represent the time-averaged behaviour of the winds. By averaging all wind speeds over the period of concern, instantaneous perturbations in the pibal measurements can be smoothed out. The method does not, however, provide a quantitative measure of the variability in age of the sampled plume parcels.

General Comments:

Comparison of a number of pibal measurements with MOE tower data suggests that large temporal changes in wind speed and direction are reasonably reflected by the pibal data. This means that Method 1 is reasonable and provides good estimates of the variability of parcel lifetime within the sampled portion of the plume.

As a check on the accuracy of the meteorological data, the plume direction for each flight was calculated using the pibal data and was compared to the actual direction of the plume given by the sampling location. In all cases, the agreement was very good.

For the September, 1976 field study, pibal data were available from Copper Cliff, Falconbridge and various locations within 100 Km. from Sudbury. In these cases, all three data sets were plotted and the most reasonable wind speed values were chosen based on flight location, consistency of data and the number of theodolite operators used to obtain the data.

The February, 1977 field study had the least number of pibal measurements of all of the studies. As a result, trajectory analyses were used quite often in the plume lifetime calculations.

The June, 1977 field study was considered to have the best temporal resolution of wind data.

Tables A2-1 to A2-3 list the plume lifetimes and the methods used to calculate them for each field study.

Plume age for runs close to the stack were estimated using a single average wind speed taken at the time of the run (Method 4).

Table A2-1:

I. September, 1976 Field Study Plume Age Estimates

FLIGHT#	RUN#	DATE	PLUME AGE	METHOD
1	2	Sept.14/76	0.04 hr.	#4
	3	Sept.14/76	0.54 hr.	#4
3	1	Sept.16/76	0.05 hr.	#4
	2	Sept.16/76	Range: 2.51-2.54 hr. Average: 2.52 hr.	#1
5	1	Sept.18/76	0.06 hr.	#4
	2	Sept.18/76	Range: 1.15-1.18 hr. Average: 1.15 hr.	#1
	3	Sept.18/76	Average: 2.02 hr.	#4
6	1	Sept.18/76	Range: 1.09-1.15 hr. Average: 1.11 hr.	#1
	2	Sept.18/76	0.07 hr.	#4
7	1	Sept.19/76	0.04 hr.	#4
	2	Sept.19/76	Range: 0.90-0.85 hr. Average: 0.87 hr.	#1
	3	Sept.19/76	Range: 1.75-2.01 hr. Average: 1.88 hr.	#1
12	1	Sept.24/76	0.03 hr	#4-only 1 set of pibal data
	2	Sept.24/76	0.56 hr	#4 available
	3	Sept.24/76	1.69 hr.	#4
	4	Sept.24/76	3.66 hr.	#4

Table A2-2:
Feb-March,1977 Field Study Plume Age Estimates

FLIGHT#	RUN#	DATE	PLUME AGE	METHOD
1	1	Feb.17/77	0.03 hr.	#4
	2	"	Range: 0.80-0.92 hr. Average: 0.85	#1
2	1	Mar.2/77	0.007 hr.	#3
	2	Mar.2/77	0.55 hr.	#3
5	1	Mar.7/77	0.16 hr.	#4
	2	Mar.7/77	Range: 0.90-0.92 hr. Average: 0.91	#1
6	1	Mar.7/76	1.60 hr.	#4
	2	Mar.7/76	Range: 2.90-3.11 hr. Average: 3.02 hr.	#1
8	1	Mar.8/76	0.002 hr.	#4,#3
	2	Mar.8/76	0.68 hr.	#4,#3
10	1	Mar.9/76	0.002 hr.	#4,#3
	2	Mar.9/76	0.15 hr.	#4,#3
12	1	Mar.10/76	0.003 hr.	#4
	2	Mar.10/76	Range: 0.59-0.60 hr. Average: 0.60 hr.	#1
	3	Mar.10/76	Range: 1.50-1.52 hr. Average: 1.51 hr.	#1
17	1	Mar.12/76	0.004 hr.	#4
		Mar.12/76	0.52 hr.	#4

Table A2-3:
June, 1977 Field Study Plume Age Estimates

FLIGHT#	RUN#	DATE	PLUME AGE	METHOD
1	1	June 3/77	0.02 hr.	#4
	2	June 3/77	Range: 0.71-0.79 hr. Average: 0.77 hr.	#1
	3	June 3/77	Range:1.98-2.00 hr. Average: 1.99 hr.	#1
4	1	June 6/77	0.009 hr.	#4
	2	June 6/77	Range: 0.93-0.70 hr. Average: 0.84 hr.	#2
5	1	June 7/77	0.003 hr.	#4
	2	June 7/77	Range: 0.75-0.82 hr. Average: 0.78 hr.	#1
	3	June 7/77	Range: 1.23-1.30 hr. Average: 1.26 hr.	#1
7	1	June 8/77	0.002 hr.	#4
	2		Range: 0.81-1.09 hr. Average: 0.92 hr.	#2
8	1	June 9/77	0.003 hr.	#4
	2	June 9/77	Range: 0.99-1.10 hr. Average: 1.05 hr.	#1
	3	June 9/77	Range: 2.08-2.46 hr. Average: 2.28 hr.	#1
10	1	June 10/77	0.07 hr.	#4
	2	June 10/77	Range: 3.19-3.40 hr. Average: 3.35 hr.	#1
	3	June 10/77	Range: 5.00-5.11 hr. Average: 5.06 hr.	#1

FLIGHT#	RUN#	DATE	PLUME AGE	METHOD
11	1	June 11/77	0.004 hr	#4
	2	June 11/77	Range: 0.88-0.93 hr. Average 0.90 hr.	#1
	3	June 11/77	Range: 4.00-4.44 hr. Average: 4.22 hr.	#1
24	1	June 21/77	Range: 1.58-1.65 hr. Average: 1.61 hr.	#1
	2	June 21/77	Range: 0.81-0.85 hr. Average: 0.83 hr.	#1
	3	June 21/77	0.004 hr	#4
26	1	June 22/77	Range: 1.50-1.53 hr. Average: 1.51 hr.	#1
	2	June 22/77	0.004 hr.	#4

Error Analysis:

Several sources of error are present in the calculation procedure; namely:

(1) Errors associated with the pibal method of wind field measurement. These errors are due to (a) sampling the wind field instantaneously instead of time-averaging (b) errors in the field measurements and smoothing techniques in the pibal system and (c) extrapolating wind speeds measured at Sudbury over long distances.

Comparison with trajectories and other pibal measurements suggests that these errors should be less than ± 20% and are typically of the order of ± 10%.

(2) Errors associated with the assumption that the centre of each flight path represents the average distance travelled by the plume.

In September, 1976, the distance was taken as that given by the operator on the flight log. The error involved could have been up to ± 10%.

In February and June 1977, the difference between the distance to the extreme edges of the traverses could be measured as well as the distance to the centre of the traverse. In February, the maximum difference between the centre and extremes of the traverse ranged from 1% to 15%. In June, the differences were somewhat smaller. Since most of the plume was not usually at the extreme edges of the traverse, it is reasonable to assume that the maximum would be typically ± 10%.

(3) The variability of lifetime of different parcels of the plume. Table I indicates that this variance can be as much as 18% of the average plume lifetime but with the exception of 2 cases, it was

typically less than ± 10%. This does not account however, for the error in the method of estimating parcel age. This error would probably be as much as 5%.

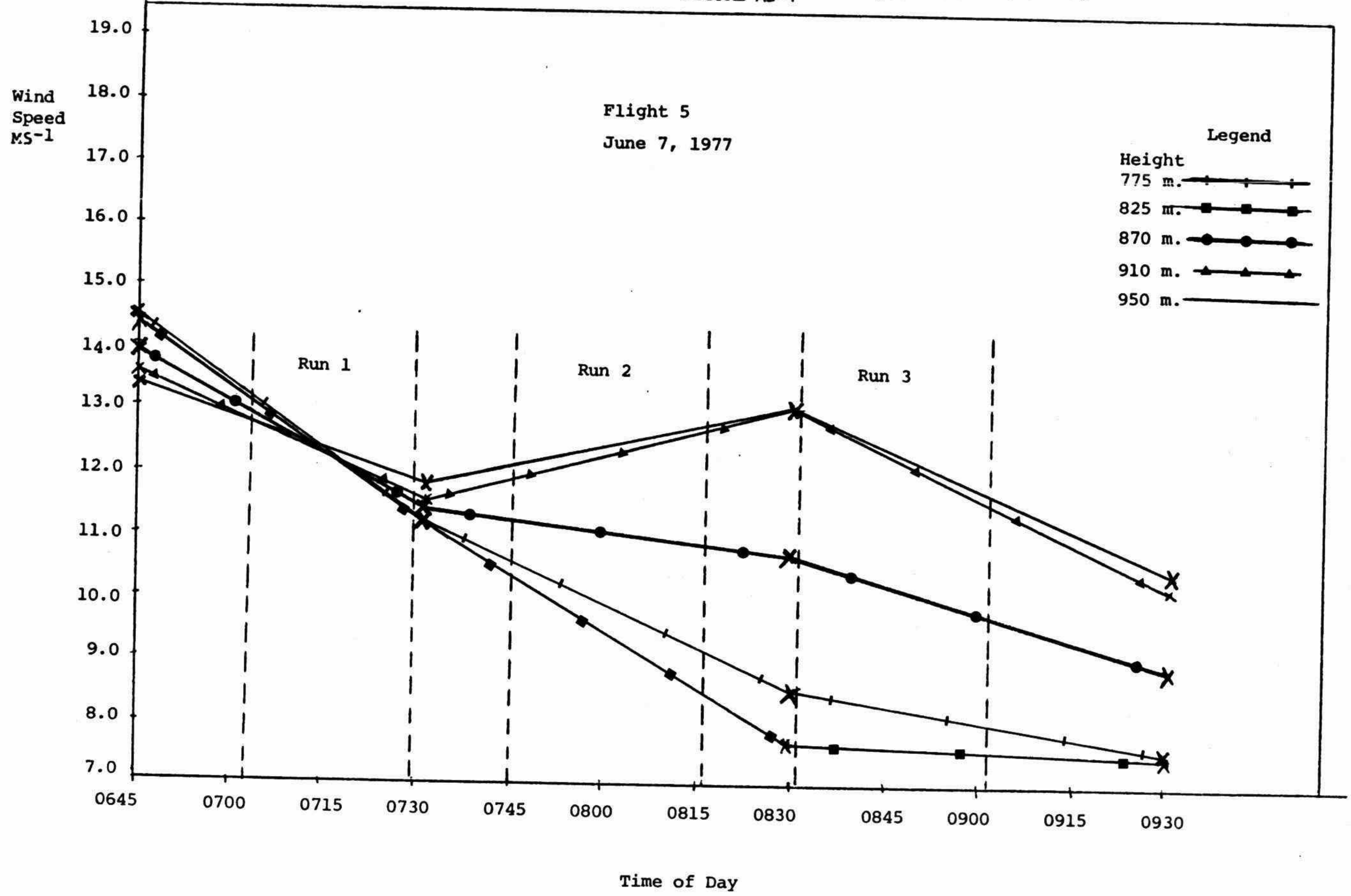
It should be noted that the variability in the age of parcels in a sampled portion of the plume is not a true error. However, it can be used to indicate the overall variation in the lifetime estimates.

Finally, it appears that the overall accuracy of the lifetime estimates is probably ± 30% but in extreme cases could range up to ± 60%.

Summary:

The plume lifetimes were calculated using the best data available and the best method for using these data. Most of these methods provided estimates of the variability of parcel lifetime in the sampled portion of the plume. When possible, data used in the calculations were checked against other data such as trajectories, tower information and plume direction information. It is suggested that the accuracy of the plume age data is typically ± 25%.

FIGURE A2-1 Wind Speed vs. Time of Day



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